Environmental assessment of the south coast of Sri Lanka, with special reference to the 2004 tsunami

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I hereby declare that the work presented in this thesis is the result of original research carried out by the author, Alicia Jane Venkatachalam under the supervision of Professor Andrew Price, unless otherwise stated. No part of this thesis has been submitted for a degree at another university.

<u>Publications of direct relevance to this thesis:</u>

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Summary

Following the 2004 tsunami in Sumatra, Sri Lanka experienced >30,000 confirmed deaths and disruption of livelihood. Damage to coastal ecosystems was less than anticipated, especially in comparison with reported impacts from unsustainable development. This research examines tsunami related damage against a background of anthropogenic pressures. Fishery changes were determined through interview of three generations of fishers targeting frigate tuna. Significantly higher values for best day's catch and largest specimen ever caught were obtained by older fishers than younger ones. Values were also significantly higher during early years, providing clear evidence of resource decline and the 'shifting baseline syndrome'. Most fishers reported post-tsunami decline in frigate tuna, but mainly from a larger new generation of fishers, rather than extra boats provided by aid money or (direct or indirect) biophysical impacts from the tsunami. The number of boats post-tsunami increased significantly in all research areas, which could result in further catch decline.

The perceptions of 500 Sri Lankan fishers about the influence of risk factors on tsunami death toll and house damage are quantified*)*. Mangroves, coral reefs and sand dunes afforded protection against tsunami damage (67–94% of fisher responses), as did housing and roads. Fishers believed rivers/estuaries, concave coastlines and hotels exacerbated impacts. For comparison, multi-variable models for death toll, housing damage, inundation area and distance are built, incorporating both natural and developmental risk factors. Bathymetry is the only factor significantly associated with all indicators of impact. Mangroves and marsh were not a significant factor in final multivariable models. However, in terms of inundation, sand dunes were identified as protective, while bodies of water exacerbated damage. The extent of agreement and variance between modelling results and the opinions of fisher questionnaires is critically examined.

Research findings highlight the need for better coastal management. While the role mangroves in tsunami protection remains equivocal, their known role in providing many other ecosystem services suggests that mangroves warrant greater conservation attention in Sri Lanka, in the face of coastal development pressures. Coastal policy and conservation priorities should be influenced by scientific research (e.g. the tsunami model in this thesis) as well as traditional ecological knowledge and opinions from

indigenous people. Factors shown to provide tsunami protection often cannot be altered by human intervention (e.g. topography and bathymetry). However, sand dunes could potentially be preserved to reduce future impacts. Tsunamis are rare events and further research should be carried out to determine which risk factors are important for more frequent events (e.g. monsoon). The needs of coastal communities should always remain paramount in considerations of future tsunami and environmental policies.

List of abbreviations

y	years
t	tonnes
IUCN	International Union for Conservation of Nature
CCD	Coast Conservation Department, Ministry of Fisheries, Sri Lanka
MFAR	Ministry of Fisheries and Aquatic Resources, Sri Lanka
NARA	National Aquatic Resources Research & Development Agency, Sri Lanka
LUPPD	Land Use Policy Planning Division, Ministry of Agriculture, Sri Lanka
UNEP-WCMC	United Nations Environment Programme – World Conservation Monitoring Centre
IWMI	International Water Management Institute
SPARC	Social Policy Analysis & Research Centre, Faculty of Arts, University of Colombo, Sri Lanka
MAP	Mangrove Action Project

1. General Introduction

The main island of Sri Lanka is located between latitudes 5°55’ and 9°51’ N and longitudes 79°4’ and 81°5’ E, comprising a total land area of 65,525 km^2 (Wijeyananda 1997; Encyclopaedia Britannica 2008) (Fig 1.1). The population of Sri Lanka is approximately 20 million and over 25% are skilled agricultural or fisheries workers, relying on the country’s land and natural resources as their primary source of income (DCS 2011). Sri Lanka has a diverse environment with varied climatic zones (CEA 1989; de Silva 1997a), sustaining many distinct ecosystems (CCD 2008). Marine and intertidal ecosystems comprise mangroves, coral reefs, sand dunes, lagoons and beaches. Together with the Western Ghats, Sri Lanka is classified as one of the world’s biodiversity hotspots, sustaining over 3000 endemic plant species, 87 endemic amphibians and over 20 endemic bird and mammal species (CI 2011).

Over recent decades both anthropogenic and natural pressures have contributed to degradation and loss of environmental systems throughout Sri Lanka. Both heavy resource use and pollution from coastal development has impacted fisheries and coral reefs (Rajasuriya & Premaratne 2000; Wijayaratne & Maldeniya 2003; Terney Pradeep Kumara *et al.* 2005). Additionally, these resources are under pressure from coral mining and sea surface temperature rises (Rajasuriya et al. 2002; Sheppard 2003), causing corals to bleach (Lowry 1994; Premeratne 2006), thus reducing the area of viable habitat for reef fish. Clearing of natural systems for aquaculture, agriculture and construction (Baan 1997) have depleted mangroves, sand dunes and beaches.

Figure 1.1 Map showing the geographical location of Sri Lanka (Mapsget 2011).

On the 26th December 2004 an earthquake occurred as the result of movement in the Australian and Eurasian plates below the Indian Ocean. A resultant 30km^3 of sea water was displaced, causing a tsunami in 19 Indian Ocean countries, with Indonesia, Sri Lanka and Thailand impacted most severely (Aeron-Thomas 2000; Gibbons & Gelfenbaum 2005; Stein & Okal 2005; Cummins & Goldberg 2006; Ghobarah *et al.* 2006). In Sri Lanka 13 of 14 coastal districts were impacted, death tolls exceeded 31,000 and over 443,000 people were displaced (DCS 2004b; ADB *et al.* 2005). Housing, tourism, fisheries, agriculture, water supply and transportation were severely impacted, with estimated damage reaching US$1 billion (de Silva *et al.* 2005; IGRAC 2006). Impacts of the 2004 tsunami on the country's ecology were variable, depending primarily on their coastal location, relative to the tsunami wave, and on the pre-tsunami health status of ecosystems (IUCN 2005a; Linden 2005, Rajasuriya *et al.* 2006).

The protective role of natural systems against coastal disturbances is widely reported (Brown 1997; Adams *et al.* 2005; Badola & Hussain 2005; Chong 2005; MFAR & CCD 2005; Sheppard *et al.* 2005; IUCN 2006b; Wells *et al.* 2006). However, the extent of protection against larger episodic events became equivocal in post-tsunami research.

Much has been debated on whether natural systems in the Indian Ocean provided protection against the 2004 tsunami and, consequently, whether areas where natural systems were heavily utilised incurring ecosystem loss were more vulnerable to impact. Reports have since been published promoting natural systems as protective (Bambaradeniya *et al.* 2005a; Bambaradeniya *et al.* 2005b; Dahdouh-Guebas *et al.* 2005b; Danielsen *et al.* 2005; Fernando & McCulley 2005; Chang *et al.* 2006; EJF 2006). Many reports relied upon eyewitness accounts or univariate statistical analysis. This has encouraged many government and non-government organisations to invest money and time in zoning the coastline, planting bioshields and in some cases, displacing residents. However, others believe the protective role of natural systems has been overstated and often miss potentially confounding factors (Baird 2006; Kerr *et al.* 2006; Kerr & Baird 2006; Baird & Kerr 2008) whilst existing multivariate research failed to find an association between natural systems and tsunami inundation (Chatenoux & Peduzzi 2005). Furthermore, there has been much criticism of post-tsunami policy relying on potentially flawed research (Rice 2005; Feagin *et al.* 2010).

The need for more research on the role of natural systems during the 2004 tsunami has been identified (Wells & Kapos 2006), as a result of the above gaps in knowledge and uncertainties. The overall aim of my research was to assess the extent to which natural environmental factors and development features influenced the outcome of the 2004 tsunami in the coastal region of Hambantota, Sri Lanka, against a background of multiple impacts. It is based on, firstly, traditional knowledge and opinions of local communities on tsunami impacts and, secondly, a multivariable statistical model considering potential risk factors and multiple indicators of tsunami impact.

Within this aim my research had a number of specific objectives. Firstly, to assess the extent to which Sri Lanka's coastal systems have been influenced by chronic and acute natural disturbances, in comparison with pre- and post-tsunami impact, with special reference to fisheries (Chapter 2 & 3). This involved literature review (Chapter 2) and a quantitative questionnaire survey to assess changes in frigate tuna populations (Chapter 3). Secondly, I quantified through questionnaire surveys, the views of fishers about factors which gave protection or which increased severity of tsunami impacts, defined as human death toll and housing damage (Chapter 4). Finally, I characterised the environment and land uses in Hambantota, Sri Lanka (Chapter 5) and, using this information, modelled the degree to which risk factors linked to natural systems (e.g. mangroves, beach slope/dune systems, coral reefs) and to development (e.g. hotels, housing) influenced tsunami damage, in terms of human deaths, house damage, inundation area and inundation distance (Chapter 6).

2. Literature review: Environmental setting of Sri Lanka, pre- and post- 2004 tsunami

This chapter is primarily a review of Sri Lanka's biophysical environment, its coastal resources and pressures. The environmental status of Sri Lanka, major ecosystems, coastal pressures and the 2004 tsunami were researched from published and unpublished sources.

2.1. Physical environment of Sri Lanka and its southern coast (Hambantota)

Sri Lanka can be divided into 6 topographical regions consisting of central highlands, south-eastern ridges, eastern and south eastern plains, uplifted lowlands, northern lowlands and the coastal fringe which is characterised by lagoons, sand bars, dunes and peninsulas (Vitanage 1997). Rainfall and wind patterns in Sri Lanka are primarily governed by the Southwest monsoon period (May-September), the Northeast monsoon period (December- February) and by two inter-monsoon periods (de Silva 1997a). Climatic periods influence weather patterns in Sri Lanka and allow classification of Sri Lanka into dry, semi dry, semi wet and wet zones which in turn dictate soil types throughout the county (Panabokke 1997).

2.2. Mangroves, algae and other coastal vegetation

Sri Lanka's coastal zone comprises diverse ecological systems including mangroves, seagrasses, beaches, marshes and lagoons (Kumar *et al.* 2004; MFAR & CCD 2005). These systems are extremely important to local people ecologically and economically, with 40% of the population engaged in activities directly dependent on the environment (Brown 1997; Primavera 1997; Tallis & Kareiva 2005; Environment Sri Lanka 2006).

Mangroves

Mangrove forests are almost exclusively tropical and comprise halophytic trees and shrubs adapted to intertidal environmental conditions. Sri Lanka currently harbours 120 km^2 of mangroves located around coastal lagoons (Kathiresan & Qasim 2005).

Worldwide 54 species of mangrove in 20 genera are known (Hogarth 1999), twenty of which are found in Sri Lanka (Jayatissa *et al.* 2002).

Mangroves are an important resource to local communities providing timber, textiles, food and medicine. Ecologically, mangroves sustain a large proportion of animal life including temporal visitors such as, birds and insects and aquatic and terrestrial organisms such as, fish, crustaceans, molluscs and reptiles (Singh & Odaki 2004; Kathiresan & Qasim 2005). They provide shelter, breeding sites and food (often in the form of leaf litter detritus). In Sri Lanka, this ecosystem service is exploited by local fishers who artificially construct mangrove thickets in lagoons to attract large numbers of fish (Hogarth 1999). Ecosystem functions and services provided by mangroves are summarised in Table 2.1.

Table 2.1 Functions provided by mangrove ecosystems (adapted from Dugan 1990).

Function	Description
Groundwater Recharge/Discharge	Water stored underground in aquifers moves upward into mangrove ecosystems providing freshwater and conversely water stored in mangroves can recharge aquifers.
Flood Control	Mangrove ecosystems are capable of storing precipitation allowing the even release of runoff (Hogarth 1999).
Shoreline Stabilisation/Erosion Control	Reducing wave energy, current or other erosive forces while simultaneously holding bottom sediment in place by plant roots (Baan 1997; Hogarth 1999).
Sediment/toxicant retention	Mangroves commonly occupy basins allowing sediment to settle. Complex aerial root systems aid this process by catching sediment in water flow. This increases the availability of saline and anaerobic sediments to sequester and detoxify pollutants.
Nutrient Retention	Removal of nutrients such as nitrogen and phosphorus from water flows improving quality and preventing eutrophication (Bann 1997).
Biomass Export	Nutrients stored in growing wetland plants are released when water cools or plants die providing nutrient rich water for wildlife (Baan 1997).
Storm Protection/Windbreak	Aids the dissipation of force and therefore lessens damage to coastal ecosystems by storms.
Micro-climate Stabilisation	Hydrological, nutrient and material cycles and energy flows of wetlands may stabilise local climatic conditions, particularly rainfall and temperature.
Water Transport	Open water habitats can serve as public transport.
Screening Solar UV-B Radiation	Possess mechanisms to deal with intense sunlight and solar UV-B radiation thus protecting the surrounding environment (Kathiresan & Qasim 2005).
Recreation/Ecotourism	Provide opportunities for sport hunting, fishing, bird watching, nature photography, swimming and sailing can be supported by wetlands.

Ecosystem functions such as shoreline stabilisation and storm protection are extremely important (Beentje & Bandeira 2007), but often overlooked. Mangroves in Sri Lanka absorb 70-90% of normal wave energy (IUCN 2005b) and are estimated to provide storm protection equating to thousands of dollars per km^2 (IUCN 2006b; Ranasinghe & Kallesoe 2006). The provision of shoreline protection in the context of the 2004 tsunami is therefore a primary theme within this thesis.

Economic evaluation is complex and necessitates detailed analysis of marketed resources, subsistence level and non-traded uses (Dixon 1989; Gunawardena &

Rowan 2005). However, many of these functions are often excluded from analysis (Table 2.2) and the resultant incomplete/poor valuation easily leads to degradation.

Table 2.2 Description of the location of goods and services provided by mangroves, indicating whether they are marketed or non-marketed services, and whether they are usually included in traditional economic analysis (Dixon 1989; Similar principles apply to coral reefs).

	Location of goods and services	
	On-site	**Off-site**
Marketed	Usually included in an economic analysis (e.g. poles, charcoal, woodchips, mangrove crabs)	May be included (e.g. fish or shellfish caught in adjacent waters)
Non-Marketed	Seldom included (e.g. medicinal uses of mangrove, domestic fuel wood, and food in times of famine, nursery area for juvenile fish, feeding ground for estuarine fish and shrimp, viewing and studying wildlife.)	Usually ignored (e.g. nutrient flows to estuaries, buffer to storm damage)

Some studies in Sri Lanka have attempted to consider both marketed and non-marketed uses of mangroves and have valued mangal forests in Kapuhenwala, at US$ 14,000 per hectare per household (Wahnbaeck & Jeanmonod 2005). Similar figures were calculated in a later study at Medagama, Medilla and Rekawa-West, considering direct household use, support to near-shore fisheries and storm protection (Ranasinghe & Kallesoe 2006). However, these high valuations of mangroves have not prevented the loss of vegetation within in Sri Lanka (Gunarathne 1997; Jayatissa *et al.* 2002) or elsewhere (Kathiresan & Qasim 2005).

Coastal resources are exploited for profit throughout the world. Mangrove clearing for conversion to agriculture (rice fields, plantations), salt ponds and the development of aquaculture are all common practices in Sri Lanka (Baan 1997). Aquaculture was first introduced in the 1980s and has become extremely popular in Sri Lanka attracting national governments and international development agencies (Gunawardena & Rowan 2005). Hundreds of approved and illicit aquaculture farms ranging from 2ha-300ha exist throughout Sri Lanka. Analysis of aerial photography has shown a close relationship between shrimp farm expansion and mangrove degradation. In 1997 culture for shrimp and fish accounted for the destruction of 20-50% of mangroves worldwide (Gunarathne 1997; Primavera 1997), In 2005 aquaculture was thought to cover 10,000 hectares of discontinuously distributed patches along SL's coast (IUCN 2005a).

Sand dunes and beaches

The beaches and dunes of Sri Lanka cover more than 11,000 ha. They are highly dynamic, changing with periods of high waves, winds and storms (MFAR & CCD 2005). These systems follow an annual cycle with considerable reductions to the ecosystem during monsoon season (MFAR & CCD 2005). Dunes are formed when sandy shores and plains dry out and sand grains are deposited in the coastal zone (Doody 2001). In Sri Lanka dunes are prominent along the coastal region. The broadest of these systems is within the Bundala Biosphere Reserve, where sand dunes vary in width from about 50 to 300 metres bordering the coastline (UNESCO 2006). They act as buffers to waves and erosion in addition to providing partial defence against wind and cyclones (Tamilnet 2002; Feagin *et al.* 2010).

Macroalgae

Assessment of marine macroalgal biodiversity in terms of species richness, taxonomic distinctness and range rarity for 66 Indian Ocean sites ranks Sri Lanka as one of the top five sites overall (Table 2.3) (Price *et al.* 2006). Biodiversity values for the algal groups individually (Table 2.4) show that Sri Lanka is the most diverse for all groups when considering Range Rarity.

Table 2.3 Summarised algal biodiversity data showing Sri Lanka to be one of five highest ranking Indian Ocean sites based on species richness (S), range rarity (R) and taxonomic distinctness (Δ+). Original study analysed a total of 66 sites (Price et al. 2006).

Locality	**Code**	***S***		***R***		**(Δ^+)**		Overall ranked values (from sum of 3 ranks)
		Value	Ranked value (1= highest)	Value	Ranked value (1= highest)	Value	Ranked value (1= highest)	
Mauritius	MU	1.17	1	148.45	4	6.1	20	1
India	IND	0.79	18	347.34	3	6.54	8	2
Aldabra Islands	AL	0.96	6	36.98	20	6.6	7	3
Bangladesh	BAN	0.79	19	48.65	14	6.7	3	4
Sri Lanka	SRI	0.85	13	116.46	5	6.12	18	5

Table 2.4 Summarised biodiversity data for individual algal groups (Chlorophyta, Phaeophyta, Rhodophyta and Cyanophyta) in Sri Lanka, showing species richness (S), range rarity (R) and taxonomic distinctness (Δ+). Xanthophyta were not present in Sri Lanka and are therefore omitted.

Algal Group	***S***		***R***		**(Δ^+)**	
	Value	Ranked value (1= highest)	Value	Ranked value (1= highest)	Value	Ranked value (1= highest)
Chlorophyta	0.65	11	26.55	5	3.44	29
Phaeophyta	0.63	7	22.29	5	3.30	41
Rhodophyta	0.76	11	62.97	5	3.76	12
Cyanophyta	0.43	18	4.66	16	3.37	17

2.3. Coral reefs: status and degradation

Distribution and diversity

In Sri Lanka three major reef habitat types have been classified including coral, sandstone and rock (Rajasuriya & Silva 1988). Fringing reefs are found along 2% of the coastline and there are numerous patch reefs 15-20 km offshore, encompassing a total area of 680 km^2 (Rajasuriya & Premaratne 2000; UNEP 2005c) (Fig 2.1). One hundred and eighty-two species of hard coral in 55 genera are known for SE India and Sri Lanka (Table 2.5). Based on this analysis, the region ranks sixth out of 26 Indian Ocean regions comparing number of species. The resources and natural defence reefs provide are vital to coastal communities (Kelleher 1997; Rajasuriya 1997). Coral mortality has been shown to increase wave energy reaching the shore (Sheppard *et al.* 2005) thus preventing erosion.

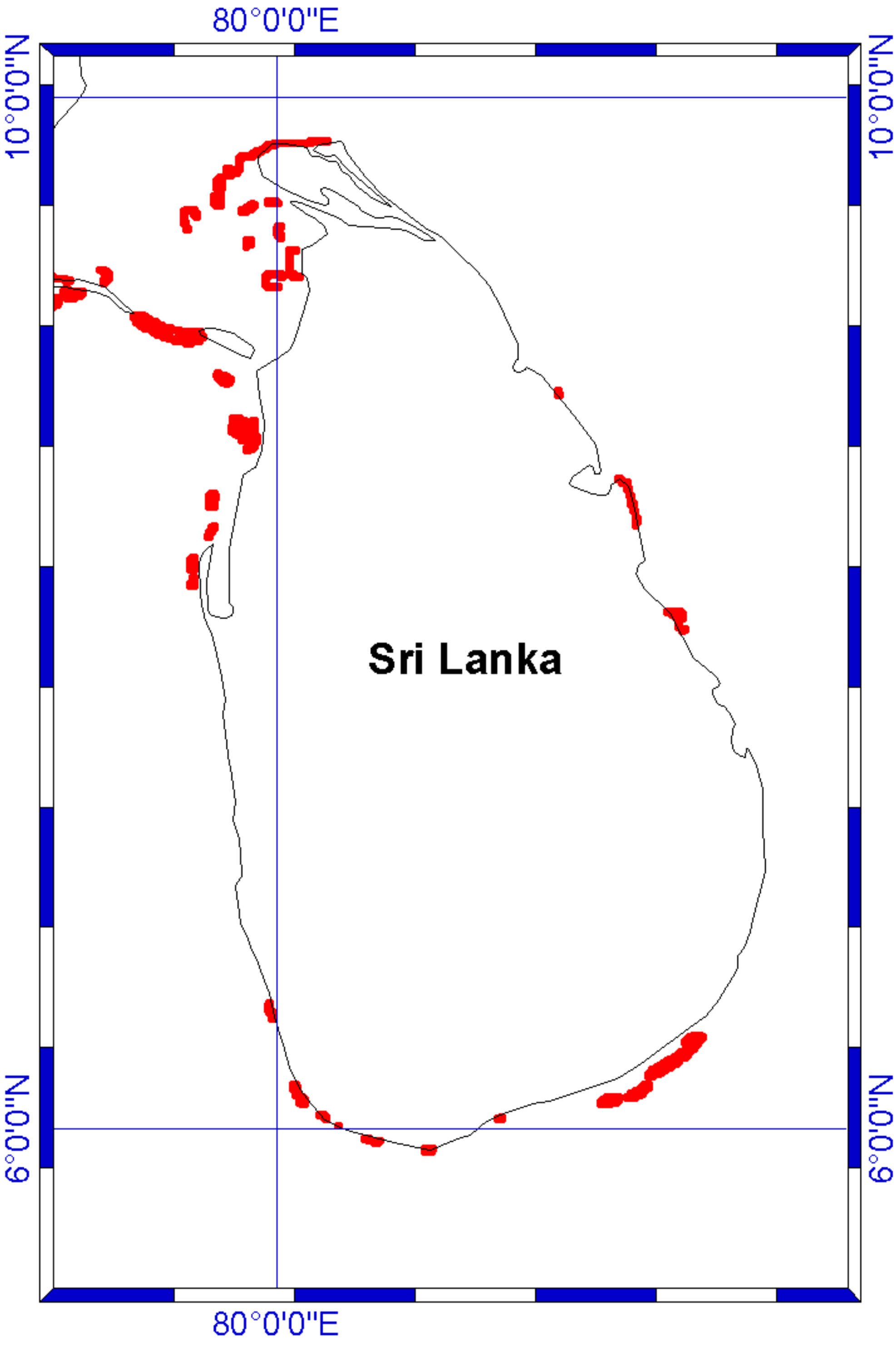


Figure 2.1 Map of Sri Lanka showing coral reefs delineated in red (Spalding et al. 2001).

Table 2.5 Patterns of coral (gamma-scale) biodiversity in the Indian Ocean shown in descending order for no. of species (Sheppard 1998).

Region	**No. of species**	**No. of genera**
All sites	491	87
NW Australia	311	71
Chagos	220	58
Thailand, Mergui Archiplelago (Myanmar)	214	64
SW Australia	192	47
Maldives	187	57
SE India, SRI LANKA	**182**	**55**
Granitic Seychelles, Amirantes	174	55
Central Red Sea (Yanbu)	150	50
Gulf of Aqaba, Gulf of Suez	138	54
Mauritius	133	47
Nicobars, Andamans	131	50
Reunion	124	43
South Red Sea Jeddah-Jizan, Sudan	115	49
Kenya/Tanzania	112	50
Tulear Madagascar	112	57
Mozambique	110	44
South Oman, Gulf of Aden, Socotra	101	43
Lakshadweeps (Laccadives)	95	34
Aldabra, Cosmoledo, Faarquhar	95	40
Cocos Keeling	94	29
South Africa	89	39
Rodriguez	84	36
Gulf of Oman	77	34
Arabian Gulf	62	27
Somalia	52	22
Gulf of Kutch	37	20

Reefs are important in Sri Lanka economically, valued at figures between 100,000-600,000 US$ km^{-2}, for the role they play in fisheries, other extractive uses, shore protection, tourism and recreation (Berg *et al.* 1998; Tamelander 2005). Important species of reef fish include groupers, snappers, emperors, barracuda, jacks, sear, leather skins and fusiliers for near-shore fisheries and butterfly fish, angel fish and pygmy angel fish for the ornamental trade (Rajasuriya *et al.* 2000). Although coral reefs are not spread wide throughout Sri Lanka, it has been suggested that 50% of the nearshore capture fisheries depend on the ecosystem (Spalding *et al.* 2001). It is estimated that 80% of the tourism infrastructure is sustained by the coastal zone and coral reefs are an important attraction for visitors to the country (Tamelander 2005). In 1994 Hikkaduwa reef in the southwest was visited by 10,000 people (Spalding *et al.* 2001).

Pressures

Coral reefs have been degraded through non-sustainable harvesting. Extraction of coral and sand for use in construction and lime production (utilised as a soil ameliorant, base for plaster and an industrial chemical) is a traditional industry in Sri Lanka, with 90% of lime derived from coral (Lowry 1994; Rajasuriya *et al.* 1995; Wickremeratne & Samarakone 1997; Premeratne 2006). Traditionally mining occurred on ancient fossilised coral reefs (Terney Pradeep Kumara 2005). However, in the last few decades harvesting of live coral from the sea has become popular, often resulting in a dramatic reduction in coral cover and decreased abundance, biomass and diversity of reef fish (Rajasuriya *et al.* 1995; Brown 1997; Terney Pradeep Kumara 2008). Studies monitoring Banduramulla reef in Southern Sri Lanka estimated that on average 66 645 kg of coral were removed from the reef when the practice was monitored between July and September 2004 (Terney Pradeep Kumara 2005). Practices such as the coir industry, where coconut fibre is extracted for the production of floor mats, brushes and bedding adds further pressure, where coconut husk pits located close to the shore contaminate lagoons with nutrient and hydrogen sulphide rich water (Perera *et al.* 2001; Terney Pradeep Kumara 2008).

Additionally, bottom-set-nets placed directly on reefs to catch lobsters and finfish cause reef damage as they are often hauled over the reefs when retrieving catch. However, the fishing practice considered most damaging is dynamite or blast fishing for both commercial and ornamental fish where large sections of reefs are damaged by explosives (Perera *et al.* 2001). Survey of dive centres along the SW coast of Sri Lanka concluded that damaging fishing practices were one of the primary causes of reef decline in terms of reef condition, coral cover and coral variety in addition to causing a decline in reef fish (Appendix 1).

Coral bleaching from analysis and modelling of sea surface temperature

Coastal ecosystems are under threat from anthropogenic pressures, however they are impacted by environmental change. Coral reefs in particular are vulnerable to fluctuations in sea surface temperature and high irradiance (WWF 1992; Brown 2006). Corals are in symbiosis with dinoflagellate algae known as zooxanthellae (Douglas 2003). Zooanthellae flourish within a specific temperature range and deviations from this range can be lethal (Sheppard *et al.* 2009). Mortality due to high temperatures and irradiance is known as bleaching, which is the result of zooxanthellae temporarily or permanently abandoning their coral host. In mild bleaching events it is possible for coral to recover, but severe bleaching often results in permanent destruction. In 1998 a severe El Nino event late-1997 followed by a La Nina event mid-1998 (Wilkinson 1998) resulted in lethal temperature excursions killing more than 90% of shallow corals on Indian Ocean reefs (Rajasuriya *et al.* 2002; Sheppard 2003; Appendix 1).

Extraction of temperatures from the historical monthly dataset provided by the Hadley Centre for Climate Prediction and Research shows that the Sea Surface Temperature (SST) in Sri Lanka is normally around 28ºC. However, in 1998 temperatures exceeded 30ºC, resulting in severe bleaching on the southern and western coral reefs. Monitoring of coral cover at four reefs in Sri Lanka (Table 2.6) showed that in 2004 there had been little recovery since the 1998 bleaching event. Improvement was seen at Weligama Reef off the south coast of the island primarily due to an increase in branching *Acropora* spp. (Rajasuriya *et al.* 2004).

Table 2.6 Coral cover (percentage) for four reefs in Sri Lanka prior to the 1998 bleaching event and in the three years following the bleaching event (n/m – not monitored) (Rajasuriya et al. 2004).

Reef Sites	Depth	Pre- 1998 beaching	1999-2000	2001-2002	2003-2004
Bar Reef Marine Sanctuary	0-3m	78.5%	Near 100% mortality	Some new colonies	17.7%
Hikkaduwa National Park	0-3m	47.2%	7.0%	12.0%	10.1%
Weligama Reef	0-3m	92%	28.0%	54.0%	70.6%
Pigeon Island National Park	0-3m	n/m	51.3%	n/m	54.4%

Minor bleaching was also observed in Sri Lanka in April 2003 and 2004 prior to the southwest monsoon however corals recovered within 3 weeks (Rajasuriya *et al.* 2004). Models predicting future sea surface temperature excursions for Sri Lanka suggest that Sri Lanka has already reached a time point where there is at least a 0.2 probability of temperatures reaching 30 °C in any given year. In some regions, such as the north-west the probability is already 0.6 (Sheppard, 2003; Appendix 2).

2.4. Fisheries and fishing in national and distant waters

Sri Lanka's fisheries are a major asset and socioeconomic activity. In 2003 the fisheries sector employed over 250,000 people and supported the livelihood of 600,000 (MFAR & FAO 2006). Finfish, snappers, groupers, spiny lobsters, sea cucumbers (DeBruin *et al.* 1994; Maldeniya & Amarasooriya 1998; Wilhelmsson 2002) and collection species for the aquarium industry (valued at US $10m in the 1990's) are particularly important in Sri Lanka (Rajasuriya *et al.* 2004). However, fishing practices are not always sustainable and many areas are over-harvested (Rajasuriya & Premaratne 2000; Terney Pradeep Kumara *et al.* 2005). Since the 1980s coastal fisheries have levelled off to 150 000-160 000 t/y (FAO 2007a) and, despite an increase in fishing effort, there appears to be little change in capture production (Wijayaratne & Maldeniya 2003). Such reduction in catch per effort is characteristic of intensifying or heavily exploited fisheries.

Because of high fishing pressures and deteriorating resources in national waters, Sri Lanka has developed distant water fisheries. These include shark and holothurian (sea cucumber) fisheries in the Laccadive Islands, the Andaman Islands, Chagos and British Indian Ocean Territory (BIOT) which has been designated a no-take zone (Graham *et al.* 2010; Price *et al.* 2010) and the world's largest marine protected area. The holothurian fishery in southern Sri Lanka began 14 years ago but soon collapsed due to lack of regulation (Terney Pradeep Kumara *et al.* 2005). In the last 15 years the BIOT Fisheries Protection Vessel has captured approximately 3 to 4 boats a year, most of which have been Sri Lankan. Both shark and holothurian fisheries in BIOT now show unmistakable signs of unsustainable harvesting (Graham *et al.* 2010; Price *et al.* 2010).

2.5. Coastal tourism

Coastal tourism is one of the largest economic activities worldwide and has contributed to the economy of Sri Lanka since the 1970s (Brown 1997). In 2004, 500642 tourists visited Sri Lanka bringing in US$416m. It has been estimated that for every 100 persons employed within the tourism sector, 140 employment opportunities are created in other sectors of the economy (Deheragoda & Tantrigama 1997; World Tourism 2006). However, both the infrastructures of coastal developments and the activities they support contribute to environmental degradation. Tourism issues in Hikkaduwa, South-west Sri Lanka for example, include inadequate waste systems to deal with increasing numbers of visitors, illegally constructed buildings on beaches, inadequate water supply, uncontrolled boating activity and over-crowding of beaches, thus contributing to pollution, sedimentation and degradation of environmental systems (Brown 1997).

2.6. Pollution

Resultant rapid urbanization of Sri Lanka's coastal zone has not always been accompanied by development of the necessary infrastructure and many environmental problems have followed (Somayajula *et al.* 2005). Resources for waste collection and disposal are lacking in most parts of the country (Zon & Siriwardena 2000) and domestic waste, industrial effluents and sewage often pollute land, water bodies, wetlands and coral reefs (Rajasuriya *et al.* 1995; MFAR & CCD 2005).

2.7. Environmental legislation and conservation in Sri Lanka

Since the 1920s there has been much interest in the management of marine and coastal resources in Sri Lanka. This has lead to the appointment of regulatory bodies and the introduction of environmental legislation. In 1978 the Coast Conservation Division (CCD) was formed within the Ministry of Fisheries. Coastal jurisdiction at this time was, however, unclear and 10 other agencies possessed overlapping responsibility (Aeron-Thomas 2000). The legislative role of the CCD was therefore formalised in 1981 by the Coast Conservation Act which provided regulatory framework for the management of activities within the coastal zone[1] (Lowry & Wickremeratne 1988; Senaratna 2006). This Act legislated that a Coastal Zone Management Plan (CZMP) be formulated, implemented and revised for Sri Lanka every four years (Zeitlan Hale & Kumin 1992). Consequently the CCD was upgraded to a Department in 1984 and by 1990 a CZMP was published encompassing policy on erosion, loss and degradation of natural coastal habitats (CCD 1990; Aeron-Thomas 2000). However, in 1992 a USAID funded project produced the Coastal 2000 document highlighting limitations to the CCD system. Many damaging practices were occurring outside the coastal zone defined within the CCD. Special Area Management (SAM) was therefore proposed and implemented as part of the 1997 CZMP (Aeron-Thomas 2000). SAM allows the comprehensive management of natural resources with the active involvement of the local community as a main stakeholder group.

The SAM process is currently active in 8 sites throughout Sri Lanka (Bar Reef, Negombo Lagoon, Lunawa lagoon, Maduganga Esturay, Hikkaduwa, Habaraduwa including Unawatuna Bay and Koggala Lagoon) and many more sites are proposed for the future (Coast Conservation Department 2005). In addition to SAM areas Sri Lanka does have protected areas. However, only three out of 146 areas are located in wetlands/the coastal zone (IUCN 2005a). A timeline of major legislation events in Sri Lanka up until 2004 is provided in Figure 2.2.

[1] The coastal zone is defined as 300m inland from mean high water mark and 2 km seaward from the low water line. When water bodies are connected to the sea, the landward limit is 2 km upstream from the sea water line.

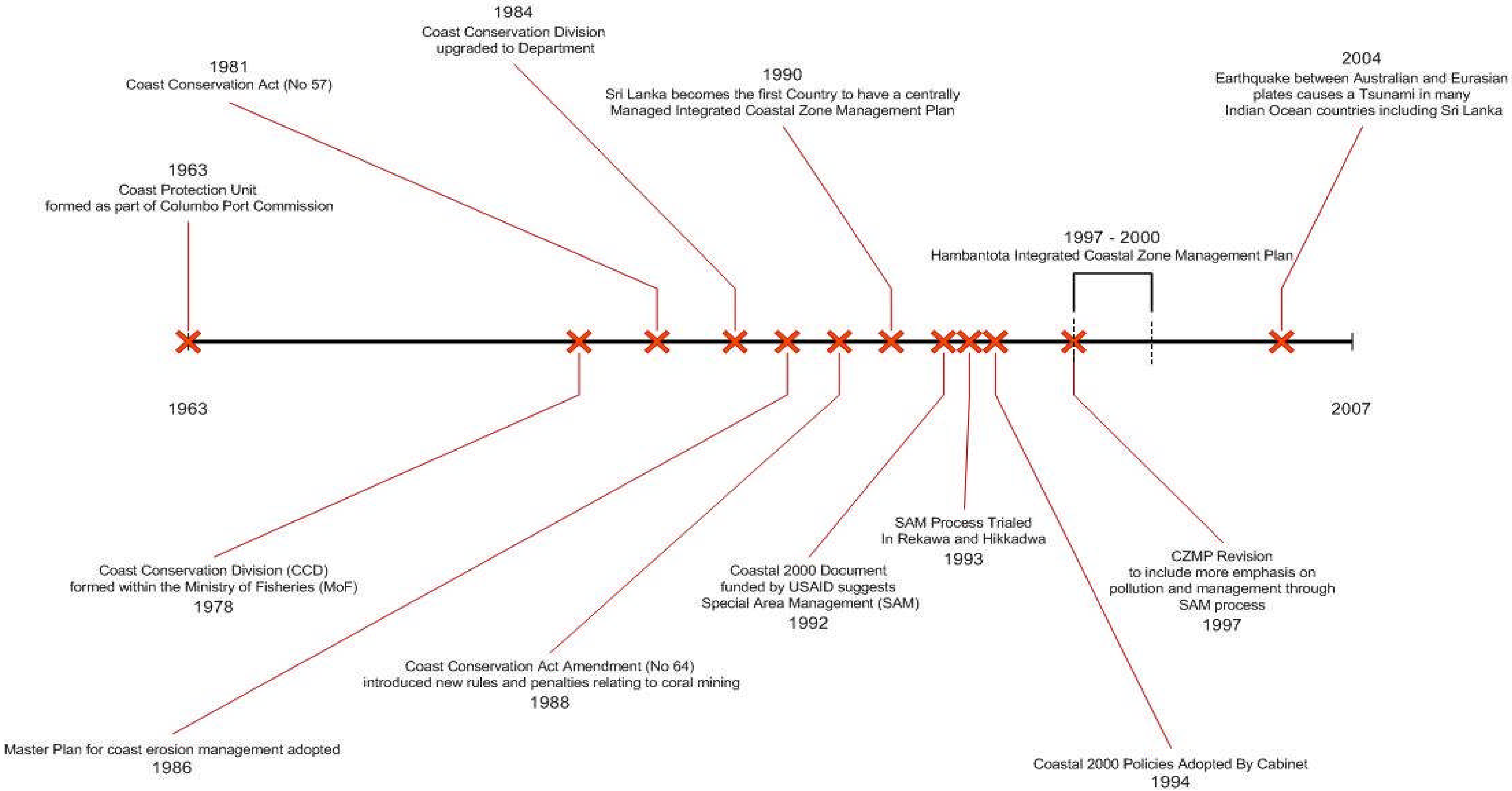


Figure 2.2 Major events in environmental legislation and appointment of regulatory bodies involved in coastal protection prior to 2004. Sourced from: (CCD 1990; CCD 2005b).

Despite many revisions to coastal protection policy, there is still often overlap and conflict between statutes and agencies (WHO 1998a). Lack of management at ground level and weak law enforcement further exacerbates this issue (De Silva 1997b; Rajasuriya & Premaratne 2000). Strict legislation to protect natural resources from livelihood activities is extremely sensitive, as there are few livelihood alternatives. Coral and sand mining for example was outlawed in 1981 by the Coast Conservation Act. However, the Mines and Minerals Act (No 3) effectively amended this policy in 1992, allowing exploration for mining, transport, processing and trade of minerals under licence (Rajasuriya 1997; Aeron-Thomas 2000; MENR 2006). Sand dunes are often owned by the government and for a small fee can be utilised or built near (UN 2006). An increasing demand for construction materials and a lack of legislation therefore sustains this destructive industry. Programmes were implemented by USAID from 1991-1996 and by Cordio and the Turtle Conservation Project in 2004 to provide alternative livelihoods to coral miners in Rekawa (Wilhelmsson *et al.* 2005). However, Rekawa was severely impacted by the 2004 tsunami and these projects were consequently disrupted. Additionally, coral mining is still more profitable than most suggested alternatives and miners have since been observed utilising large rafts to bring coral ashore (Rajasuriya *et al.* 2004).

Sri Lanka is party to many international conservation treaties and conventions, including the World Heritage Convention, Convention on Biodiversity (CBD), Bonn Convention (migratory species), Ramsar Convention (wetlands). It is also party to the UN Convention on the Law of the Sea (UNCLOS) as well as the Framework Convention on Climate Change (FCCC). Despite national and international environmental legislation, the environment of Sri Lanka has deteriorated severely in recent decades (Rajasuriya *et al.* 1995; Brown 1997; Gunarathne 1997; Rajasuriya & Premaratne 2000; Jayatissa *et al.* 2002; Terney Pradeep Kumara *et al.* 2005; Terney Pradeep Kumara 2008). This has implications for the consequences of future disturbances, including any chronic environmental changes and episodic events such as storms and *tsunamis*.

2.8. The 2004 tsunami: impacts, environmental risk factors and policies

Main events

The Sumatra-Andaman earthquake occurred at latitude 3.3º' N at 00:58:47 Coordinated Universal Time (UTM) (Spencer 2007). The resultant tsunamis that radiated around the Indian Ocean affected 19 Indian Ocean countries, resulting in loss of life, destruction of property and environmental damage. Indonesia, Sri Lanka and Thailand were impacted most severely (Ghobarah *et al.* 2006; Wilkinson *et al.* 2006). Eyewitness tsunami accounts from Sri Lanka reported up to three waves, with the first two arriving 2-3 hours after the earthquake and the third after 6 hours (Liu *et al.* 2005). Besides the more obvious impacts, the tsunami had many indirect effects, some of which are examined in this review and later sections of the thesis.

Human and economic loss

The overall loss to human life and settlement throughout the Indian Ocean was profound with approximately 250,000 lives lost and millions of people displaced. Damage was estimated by the UN Humanitarian Flash appeal to exceed $10 billion with economic loss from housing, tourism, fisheries, agriculture and transportation (UNEP 2005a).

In Sri Lanka alone (where 13 of 14 coastal districts were impacted), death tolls exceeded 31,000 and over 440,000 million people were displaced by the disaster (DCS 2004b; ADB *et al.* 2005). Damage in Sri Lanka was estimated at US$1 billion by the World Bank (de Silva *et al.* 2005). Coastal housing was impacted with 13% damaged or completely destroyed (IUCN 2005a).

Livelihoods of millions of people in tsunami ravaged countries were disrupted, with over 200,000 livelihoods and 125,000 jobs lost or disrupted in Sri Lanka (TAFREN 2007). Those dependent on ecosystem services and natural resources, such as fishers and farmers, were worst affected (UNEP 2005a). The fishing industry suffered major losses in boats, nets, culture ponds, cages and shrimp hatcheries (UNEP 2005b; UNEP 2005d). The 2004 tsunami affected 90% of Sri Lanka's fishers, taking 7600 lives, destroying 80% of fishing vessels and damaging equipment and homes (FAO 2005b; ITDG 2005; OCHA 2005). Pre-tsunami (2003) the fisheries sector of Sri

Lanka employed over 250,000 people and supported the livelihood of 600,000 bringing in a catch of 284,960 t (MFAR & FAO 2006). However, in 2005 fish catch declined to 163,230 t (MFAR 2006).

The agricultural sector was heavily impacted from saline intrusion of soil and groundwater (UNEP 2005b; Chandrasekharan *et al.* 2008). Toxicity of groundwater and osmotic stress led to crop failure (FAO 2007c), evidence of which was witnessed in Indonesia, where rice crops were seen to yellow within three weeks of the tsunami (UNEP 2005d). In Sri Lanka the Ministry of Urban Development and Water Supply (MUDWS) estimated that 12,130 fresh water wells were damaged, resulting in scarcity of drinking water and shortages for agricultural purposes (IGRAC 2006).

Environmental impacts

In addition to the direct impact to human population and infrastructure, the tsunami was responsible for damage to the coastal environment. Areas close to the epicentre suffered extensively. Coastal erosion caused by tsunami waves affected a range of countries both close by and further away from the epicentre. In the Chagos Archipelago, to the south, the tsunami is estimated to have accelerated erosion by 1-2 years on the eastern coast (Sheppard 2007). Alteration of beach and lagoon morphology was prominent in Sri Lanka, with some lagoon channels deepened whilst others were blocked by debris (IUCN 2005a; IWMI 2005). Lunam-Kalametiya Mangrove Sanctuary, for example, was transformed from a closed system to an open system when a sandbar was washed away (Atapattu 2005).

Coral reef impacts varied dramatically between sites throughout the wider Indian Ocean, and between localised sites (in some cases separated geographically, by as little as a few meters) (Campbell *et al.* 2006; Phongsuwan & Brown 2007). Damage was typically observed in three forms; (1) overturned coral; (2) mechanical damage constituting broken pieces of coral; and (3) sedimentation: run-off from land being washed onto reef (Hagan *et al.* 2007). Corals attached to unconsolidated substrata were impacted most severely, subjected to overturning, burial and transportation (Baird *et al.* 2005; IUCN 2005a). This was most commonly observed amongst massive *Porites* colonies and table *Acropora* sp. whereas breakage was often observed in branching corals (Hagan *et al.* 2007; Phongsuwan & Brown 2007).

Much of the mechanical damage occurred when natural and man-made materials (including trees, vehicles, fuel tankers, silt and debris) were dragged into the open ocean (UNEP 2005d; NARA 2007). In general, reef and coral damage by the tsunami was considered to be mild in comparison with anthropogenic disturbances (Wilkinson *et al.* 2006).

Changes in water depth occurred in some Indian Ocean locations, following the tectonic movements which caused the 2004 tsunami, resulting in sub-aerial exposure of reefs. For example, in Banda Aceh Indonesia, the shoreline moved inland 1.5km and in both Aceh and Andaman some fringing reef flats were uplifted 1.5-2 metres resulting in sub-aerial exposure (Brown 2005). This caused increased temperature and sunlight exposure and, not surprisingly major impact to reefs (Borrero 2005; Brown 2005; Brown 2006; Hagan *et al.* 2007).

Coral damage in Sri Lanka was highly variable, affecting reefs on the east and south coast most severely (Fig 2.3). Corals facing the open ocean sustained more damage than those within lagoons. Mechanical damage was caused by the movement of sections of reef, boulders and smaller fragments and by tsunami backwash carrying debris from the land (Linden 2005; Wilkinson *et al.* 2006). Extreme mechanical damage was reported at 15-30% of several hundred sites observed on the southwest and east coast of Sri Lanka and the Andaman Sea coast of Thailand (Linden 2005). Average live coral cover was reduced by 14% (52% to 38%) along the east coast whereas the south and south west coast experienced variable reductions in cover ranging from 3.5% to 18% (Rajasuriya *et al.* 2006).

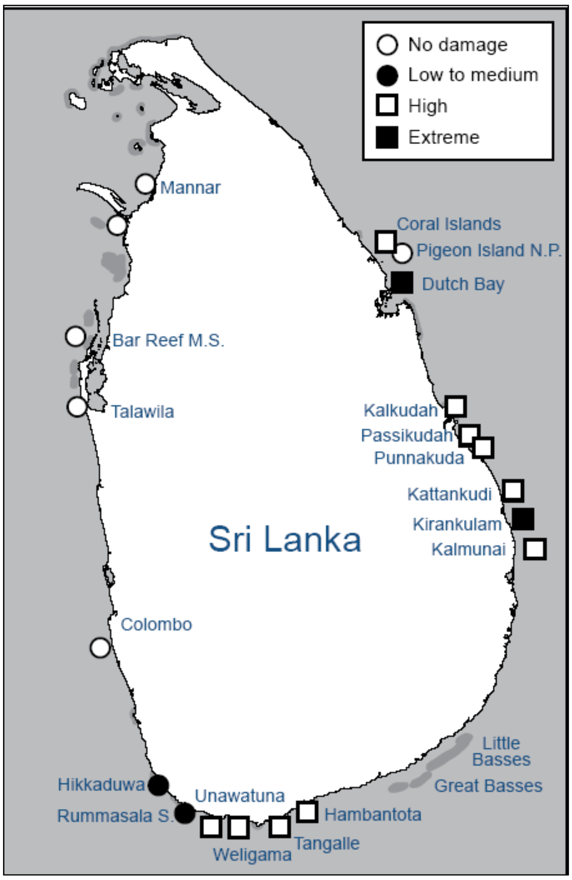


Figure 2.3 Coral reefs affected by the tsunami around the coast of Sri Lanka, indicating systems which experienced low, high and extreme tsunami damage (Rajasuriya et al. 2006).

In Sri Lanka a reduction in species composition and fauna encompassing amphibians, reptiles, birds, butterflies and molluscs was observed through rapid assessment (Bambaradeniya et al., 2005b). Surveys undertaken immediately after the 2004 tsunami reported a decline in small coral associated fish (Rajasuriya *et al.* 2006). However, in Aceh, Northern Sumatra research has shown that reef fish assemblages were not affected (Campbell *et al.* 2006). Adult turtles were washed inland as far as 5km and nesting sites were severely damaged (Riminton 2005). In Bentota for example, 20,000 eggs were washed away (Wickramasinghe 2005). Similarly, nesting sites for temporal and resident birds were lost. In Northern Brother atoll, Chagos, no young Brown Boobies were observed in February 2005, reflecting tsunami impacts on the nesting sites and breeding activity (Sheppard 2007). Impacts to flora were also variable; mangrove damage depended upon the maturity of the wetland system. Larger mature trees were more resilient to the water surges, although in some areas even these were uprooted (IUCN 2005a). Despite considerable short-term damage the effect of the 2004 tsunami on ecosystems was thought to be less than expected (Brown 2006; Wells & Kapos 2006).

Environmental degradation: a tsunami risk factor?

Loss or degradation of natural habitat and changes in biodiversity to a system are likely to play a role in their resilience to recurrent disturbances, including episodic events such as storms and *tsunamis*. Coral reefs, wetlands and dune systems have been reported to dissipate wave energy and play a protective role against episodic and other disturbances (Brown 1997; Adams *et al.* 2005; Badola & Hussain 2005; Chong 2005; MFAR & CCD 2005; Sheppard *et al.* 2005; IUCN 2006b; Wells *et al.* 2006).

Degradation of ecosystems, such as coral reefs, mangroves and sand dunes in Sri Lanka, may therefore have resulted in a weakened natural defence against the 2004 tsunami. Conversely, healthy coastal systems may have provided protection. These are among the central themes examined in my research. Experimental and theoretical models suggest mangroves reduce tsunami impact by decreasing hydraulic force (Mazda *et al.* 1997; Harada *et al.* 2002; Alongi 2008). Visual observations and eyewitness accounts from countries affected by the 2004 tsunami suggest that natural systems saved lives and reduced damage to infrastructure (Bambaradeniya *et al.* 2005a; Brosnan 2005; IUCN 2005b; Kar & Kar 2005; Wabnitz *et al.* 2005; WI 2005; Dahdouh-Guebas 2006). These reports suggest that mangroves and reefs dissipated wave energy, coastal lagoons absorbed tsunami waters, and that sand dunes functioned as barriers against inundation. Vegetated coastal sand dunes in Yala and Bundala National Parks, Sri Lanka, appeared to completely obstruct the tsunami. Similarly, areas of dense broad mangroves experienced little damage compared to cleared areas (Atapattu 2005; Bambaradeniya *et al.* 2005b; IUCN 2005a).

The role of mangroves and coral reefs, in particular, became equivocal in post-tsunami research. Experimentally, correlations between extent of mangrove systems (i.e. coastal vegetation, reef cover, sand dunes) and tsunami impacts (including wave inundation, community death toll, plantation destruction and structural damage) were established in India, Sri Lanka and Thailand (Danielsen *et al.* 2005; Kathiresan &

Rajendran 2005; Chang *et al.* 2006; Cochard *et al.* 2008). One study comparing four sites (Medagama, Medilla, Netolpitiya-south and Rekawa-west) in Hambantota, Sri Lanka concluded that sites behind mangroves incurred fewer damage costs in terms of loss to agricultural crops, human injury and subsequent income decline during their period of disability (Ranasinghe & Kallesoe 2006). Modelling of tsunami damage in Aceh revealed developed areas were far more susceptible to tsunami damage than forested land (Iverson & Prasad 2007; Iverson & Prasad 2008). Similarly, GIS work in Thailand revealed mangrove ecosystems appeared to suffer fewer impacts than other vegetation (Sirikulchayanon *et al.* 2008). However, other studies consider the protective role of mangroves to have been overstated, suggesting elevation, exposure and distance inland may have been more significant, claiming a 10 m high wave was only prevented from further encroachment by the 10m high contour (Baird *et al.* 2005; Baird 2006; Kerr *et al.* 2006; Kerr & Baird 2006; Baird & Kerr 2008). Studies have also been identified as failing to address possible risk factors such as, variation in house construction when examining structural damage (Dahdouh-Guebas *et al.* 2006). The protective role of corals in Sri Lanka determined by examining damage behind heavily mined sites (Fernando & McCulley 2005) has similarly been questioned (Baird *et al.* 2005).

Research has also associated the protective capacity of natural systems with their health, assuming a cause-effect relationship. In the course of the tsunami, Hikkaduwa National Park, Sri Lanka, experienced relatively low changes in fish abundances in comparison to non-protected areas along the same coast (Chavanich *et al.* 2005). Additionally, a hypothesis based on observation on the Baticaloa lagoon, Sri Lanka predicted an undisturbed system would decrease tsunami waveform upon impact and absorb excess water; however, a degraded system may result in wave amplification (Manobavan 2005). Another study examining mangrove extent and health in relation to tsunami impact (Dahdouh-Guebas *et al.* 2005b) invoked that those with least disturbance were most resilient, thereby providing greatest protection. Again, however, much of this research did not consider the potential influence of confounding factors. Reanalysis of the relationship between mangrove health and damage (Baird 2006) revealed that the observed pattern of damage was not different from that expected by chance and cannot be linked, unequivocally, to pre-tsunami forest condition (Kerr & Baird 2006).

Chang *et al*. (2006) attempted to reduce the possibility of confounding factors by comparing location pairs with varying degrees of mangrove degradation, but similar biophysical characteristics. This research concludes mangroves do appear to provide an effective buffer against tsunami forces (Adams *et al.* 2005; Chang *et al.* 2006). However, multivariable modelling (Chatenoux & Peduzzi 2005), using maximal flooded distance as a proxy for tsunami impacts indicates that wave height and elevation were more important determinants of protection than natural systems. Their study encompassed 56 sites and was based on analysis of multiple variables including distance from tectonic activity, angle of waves with the coastline, shore elevation, bathymetry, and presence of coral, mangroves, seagrass and coastal degradation. Although seagrasses were shown to have a small protective role, natural systems did not appear to be an important influence on reducing maximal flooded distance. Furthermore, coral reefs were shown to increase the maximal flooded distance i.e. exacerbated tsunami impact. Other natural systems have also been reported to have exacerbated tsunami impact. Eye witness reports in Thailand, for example, suggested that mangroves deflected initial tsunami waters into subsequent waves contributing to a larger more powerful tsunami (pers. comm. Kendall 2006). Similarly, settlements in Kampuan Village, Ranong Province Thailand were inundated from 2 different directions, a possible consequence of mangal forests focusing tsunami wave energy up-channel (Kendall *et al.* 2005).

Overall, there is a lack of agreement between studies investigating the importance of coastal systems in providing tsunami protection. Further research is therefore necessary to clarify their role in shore protection and to identify the principle factors that influenced the intensity of tsunami induced damage (Wells & Kapos 2006). Mangroves, coral reefs and other environmental systems and features are therefore evaluated as potential tsunami risk factors in this thesis (Chapters 4-6).

Post-tsunami policy in Sri Lanka

In the aftermath of the 2004 tsunami the Sri Lankan government re-enforced and updated sections of the 1981 Coast Conservation Act No.57. The main outcome of this was the implementation of a buffer zone, within which development would be restricted in the future (CCD2005a). It was declared that a 100m buffer zone from the permanent vegetation line of the beach front should be delineated for any new construction in the west and south coast (from Kala Oya river mouth-Gange Wadiya to Kinindi Oya river mouth). Similarly, a 200 m buffer zone from the permanent vegetation line of the beach front should be delineated for any new construction in the east and the north coast (from Kinindi Oya river mouth to Kala Oya-Gange Wadiya (CCD 2005a). Certain projects would be considered for exemption from this setback zone if they satisfied one of the following categories:

- Were of national importance
- Fisheries related buildings and infrastructure (excluding dwellings)
- Tourism related developments within declared tourism zones

Post-tsunami reconstruction would also be restricted by this legislation. Buildings and houses located within the coastal zone which were damaged or destroyed by the 2004 tsunami would therefore need to be relocated further inland. Private land within this zone would remain the property of owners, but many people from fishing communities and those engaged in other near shore activities were initially prohibited from rebuilding their homes (Leckie 2005; Rice 2005). These setback zones would protect people from future tsunami, storm and monsoon damage and could potentially aid recovery of the degraded coastal zone. However, the social and economic impact of this legislation was severe (Harris 2005). The coastal zone is densely populated and there is limited space inland for resettlement. Additionally, many coastal communities rely on natural systems as a source of livelihood and are engaged in fishing and agriculture. Additionally, tourism projects were often permitted within the setback zone (Rice 2005). The setback zone was eventually relaxed after the Ministry of Urban Development and Water Supply identified these issues (Samaranayake 2005) but a large number of people had already relocated.

Much of the post-tsunami efforts have been focused on restoring and improving infrastructure (Emerton 2006). However, projects implemented by the Coast Conservation Department in Sri Lanka do include the reconstruction of protective structures, rehabilitating sand dunes and establishing a green belt along the coastline. NGOs, have also been involved in projects, encouraging the replanting of mangrove ecosystems in tsunami affected regions (Photo 2.1) (IUCN 2006b). This financial investment and potential socio-economic disruption, resulting from the post-tsunami projects (e.g. bioshield planting), further supports the need for research into their potential role in protection.

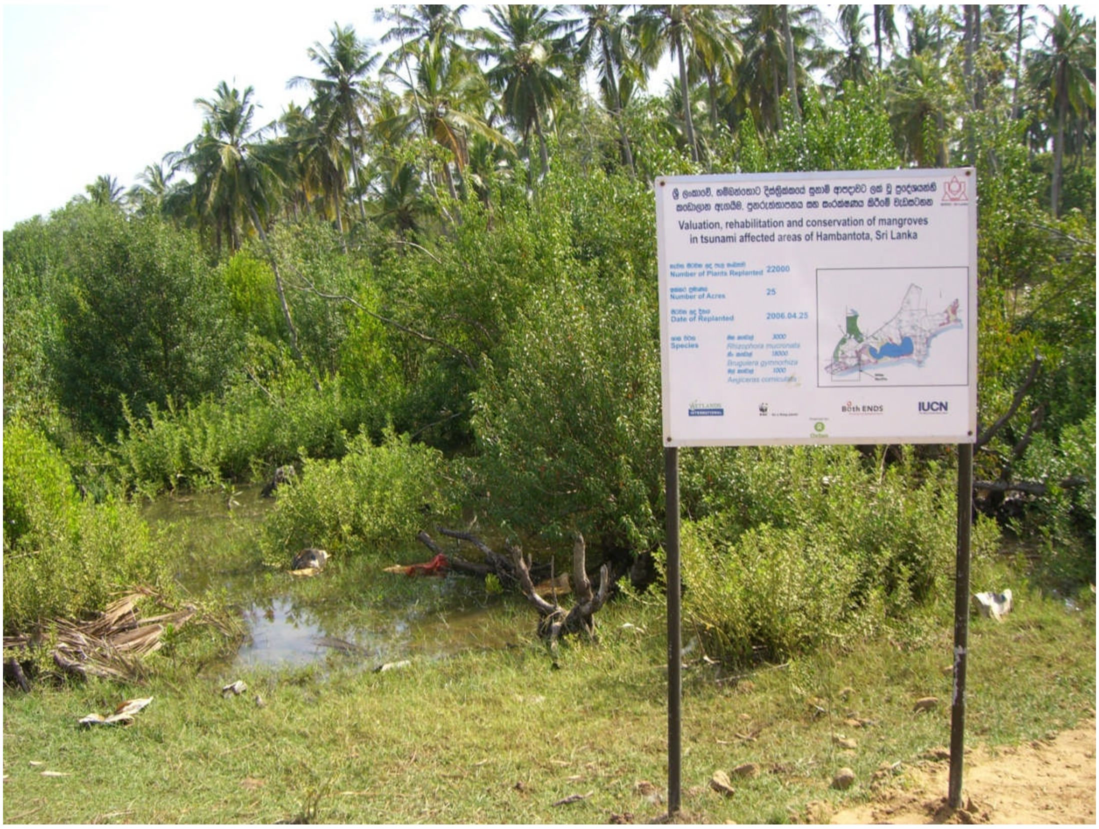


Photo 2.1 Mangrove replanting schemes have been initiated by the IUCN and other organisations along the SW coast of Sri Lanka. This photograph shows an area where replanting has occurred under the 'Valuation, rehabilitation and conservation of mangroves in tsunami affected areas of Hambantota, Sri Lanka' project.

3. Frigate tuna populations on the south coast of Sri Lanka before and after the 2004 tsunami: analysis of fisher observations

3.1. Introduction

3.1.1. *Background information on frigate tuna and fisheries in Sri Lanka*

Sri Lanka's Exclusive Economic Zone (EEZ) encompasses 517,000 km^2 and national coastal/fishing waters extend to approximately 70 km offshore. The fishing industry contributes to approximately 2% of the country's national income and annually produces c. 250,000 t of fish (ITDG 2005; FAO 2007a). Tuna fisheries have developed rapidly in recent years (FAO 2007b). These are based on frigate tuna (*Auxis thazard*) and eight other tuna species, including skipjack (*Katsuwonus pelamis*) and yellowfin tuna (*Thunnus albacares*). Snappers, groupers, spiny lobsters and sea cucumbers constitute other important fisheries (DeBruin *et al.* 1994; Maldeniya & Amarasooriya 1998; Wilhelmsson 2002).

This chapter focuses on frigate tuna (*Auxis thazard*), a coastal resource of longstanding importance in Sri Lanka (Dayaratne 1993). Frigate tuna are found worldwide in tropical and subtropical waters. While basic ecological and life history details have been summarized for frigate tuna worldwide (Uchida 1981), little published information appears to be available for Sri Lanka, where its distribution includes the southern (Hambantota) region. The species is mainly insular, with a localized migratory habit primarily restricted to continental shelves (Sivasubramaniam 1984; Maguire *et al.* 2006). In southern Sri Lanka, harvesting certainly occurs close inshore, as shown in this chapter. In southern Sri Lanka frigate tuna adult (and possibly sub-adult/juvenile) populations are vulnerable to harvesting pressures. Certain life cycle phases are potentially also susceptible to environmental disturbances arising naturally (e.g. tsunami impact) or from coastal development activities.

3.1.2. *Pressures on Sri Lanka's fisheries*

Sri Lanka's population densities are high (often 100-500 km^{-2}), reaching 2,900 km^{-2} near Colombo (SEDAC 1997-2006). This has created significant strain on local (and distant) fishery resources, both fin-fish and invertebrates. Many coastal and marine areas are over-harvested (Rajasuriya & Premaratne 2000; Perera *et al.* 2001; Terney Pradeep Kumara *et al.* 2005; Stobutzki *et al.* 2006). Evidence includes decline in catch per effort (Wijayaratne & Maldeniya 2003; FAO 2005d) and in fish size (MFAR & CCD 2005). Both are characteristic of intensifying or heavily exploited fisheries (Hillborn & Walters 1992; Pauly 1994). Additionally, ecosystems such as coral reefs are damaged by bottom-set nets and dynamite fishing, as well as by coral mining, resulting in extensive physical damage.

The full influence of harvesting in Sri Lanka, as elsewhere, is often hindered by the short time-series of many of the datasets on fishery catch statistics and by the grouping of major species in monitoring programmes (e.g. Saenz-Arroyo *et al.* 2005a; Saenz-Arroyo *et al.* 2005b). One means of overcoming constraints imposed by limited scientific data sets is to tap into the memories of fishers, an approach linked to the emerging 'discipline' of historical ecology. The valuable information possessed by subsistence communities about natural resource assessment, ecology and management is well documented (Inglis 1993; Johannes 1998; Johannes *et al.* 2000). Particularly significant is the 'shifting baseline syndrome', which describes how perspectives change as one generation replaces another, such that the extent of past environmental modifications by humanity or other changes easily slip by, unnoticed or unrecorded scientifically (Pauly 1995; Saenz-Arroyo *et al.* 2005a; Saenz-Arroyo *et al.* 2005b). Intuitive knowledge and community actions can also be helpful at times of natural disasters (e.g. Kumara 2005). This has been recently reported for coastal communities in Sri Lanka, following the 2004 tsunami (Senaratna 2006; Senaratna Sellamuttu and Milner-Gulland 2005; Venkatachalam *et al.*, 2009).

This chapter assesses the status of frigate tuna fisheries on the southern coast of Sri Lanka. The assessment is based principally on opinions of artisanal fishers who use mostly driftnets to catch frigate tuna (Senaratna 2006). The chapter tests the assertion that prolonged and increasing exploitation of frigate tuna populations in Sri Lanka may have exerted a discernible influence on abundance.

Specific major objectives are to: (1) provide a brief description of Sri Lanka fisheries as a context for this chapter; (2) examine changes in frigate tuna populations, based on fisher perceptions and ‘shifting baselines’ over a 30-40 y period; (3) determine, for comparison, changes in catches from fishery catch statistics (over a shorter time-period). A secondary objective, again based primarily on fisher opinions, is to evaluate the significance of possible tsunami related factors on frigate tuna populations. The chapter also discusses the potential role of fisher observations and significance of the shifting baseline syndrome as an input to marine resource management. It concludes with measures that may help lead Sri Lanka down more sustainable resource-use pathways.

3.2. Methods

3.2.1. ***Study area for questionnaire survey***

Questionnaires (Appendix 3, *Questionnaire 2*) were administered to fishers along the southern coast of Sri Lanka in the Tangalle DS (divisional secretariat) region of Hambantota. A community was selected within each of Medilla, Kahadamodara and Mawella Grama Niladhari (GN) divisions. (This is the smallest administrative unit in Sri Lanka, of which there are 19 bordering the coast in Tangalle.) Additionally, two communities in Gurupokuna were interviewed, making a total of 5 communities in 4 GN divisions (Fig 3.1). The southern coast was selected for study as it is an important area for tuna and other large pelagic fisheries (Joseph & Moyiadeen 1986; De Silva & Yamao 2007). Tangalle is also one of 25 major fishing districts used by the Ministry of Fisheries and Aquatic Resources to report statistics. Additionally, fishers within Tangalle were severely affected by the 2004 tsunami (Senaratna Sellamuttu & Milner-Gulland 2005; Senaratna 2006; Venkatachalam *et al.* 2009). Despite an influx of government, local and international donations (De Silva & Yamao 2007), fishers reported an 18% drop in monthly income post-tsunami and a downwards shift in their perceived wealth (Chapter 4; Venkatachalam *et al.* 2009).

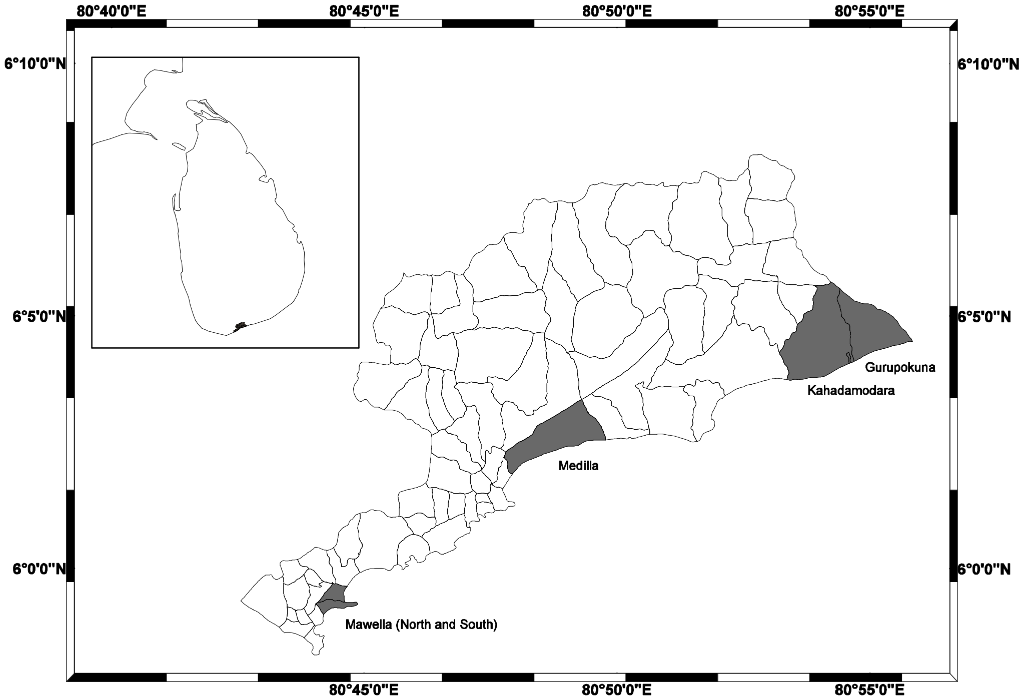


Figure 3.1 Map of Sri Lanka showing Tangalle DS (Divisional Secretariat), the study area on the south coast (inset) and the 4 GN divisions sampled within Hambantota region (from Social Policy Analysis and Research Centre, University of Colombo, Sri Lanka).

3.2.2. *Sampling strategy*

A sample of 120 fishers within three age classes (below) was used for the questionnaire survey, and interviews were held over several weeks in April 2007. The sample encompassed 28%, 35%, 44% and 99% of the total population of coastal fishers for Mawella, Madilla, Kahadamodara and Gurupokuna respectively (MFAR 2008). Interviewers randomly approached fishers along the beach front and visited fisher homes.

3.2.3. *The questionnaire*

Initially, a pilot questionnaire was administered to 10 fishers in Kalametiya and Rekawa on 10 and 11 March 2007. Pilot questionnaires were primarily carried out to ensure questions were understandable and units/scales (e.g. inches, kilograms) were appropriate. During pilot interviews fishers were originally asked to describe their best ever catch and the year they remember landing it. However, it became apparent that respondents preferred to give their age at this time rather than a specific year. The questionnaire was then adjusted accordingly.

The final questionnaire (Appendix 3) consisted of two sections. First, information which, collectively, might indicate any changes in frigate tuna populations. This included best day's catch and largest fish ever caught by fishers, and their age at the time. Fishers were also asked for information on distance offshore, and water depth, associated with their best catch of frigate tuna, and to record the number of fishing locations showing a decrease in catch. Questions in the second part of the questionnaire asked fishers (directly) for their opinions on any changes to frigate tuna stocks, and whether this resulted directly or indirectly from the tsunami, or other causes such as climate change. Respondents were then asked to report the number of boats within their community before and after the 2004 tsunami.

Interviews were carried out by a team of trained academics and research students from the University of Colombo. Ethical and technical standards were followed in accordance with Bunce *et al.* (2000). Local residents often accompanied researchers to gain the confidence of respondents (Senaratna Sellamuttu & Milner-Gulland 2005). Interviews were conducted in private to ensure fishers were not influenced by responses of others.

3.2.4. ***Questionnaire data analysis***

A total of 120 questionnaires were completed by fishers. All fishers approached were male as men comprised 99% of fishers in 2003 (FAO 2005c). Respondents were asked their age in years, which was later placed into one of three age-groups (15-30, 31-54 and ≥55 y) for comparison. Data were analysed using SPSS 14.0 (SPSS Inc. 1989-2005) and STATA SE 9.2 (StataCorp LP 1985-2007).

Medians and inter-quartile range for the various catch parameters were calculated for the three age categories. Differences between age groups for parameters were determined using a non-parametric test for trend, an extension of the Wilcoxon rank-sum test (Jack 1995). Correlations between catch parameters and actual age were also assessed, using Spearman's Rank correlation test. Categorical variables (number of sites depleted) were compared by chi-square test of association. Besides comparing frigate tuna catch parameters (best day's catch, largest fish, etc.) by age category, separate analysis was undertaken to determine strength of association with year.

Descriptive statistics were used for fisher opinions on changes in catch since the 2004 tsunami. The number of boats, pre- and post-tsunami in each of the GN divisions was compared by the Wilcoxon Signed-Rank test ($p \leq 0.01$).

3.2.5. ***Frigate tuna catch statistics***

National catch data on frigate tuna from 1982-2007 tuna were extracted from Indian Ocean Tuna Commission (IOTC) datasets. IOTC catch and fishing effort data (1994-2004) for frigate and bullet tuna (combined) were obtained for south-eastern Sri Lanka, the region approximating to that of the questionnaire survey. Frigate tuna is believed to be the dominant species in catch statistics (Sivasubramaniam 1985). Effort data are a combination of statistics reported by national intuitions, liaison officers and estimates based on the IOTC sampling programme. Monthly catch per unit effort (CPUE) was calculated and averaged to give an overall CPUE value for each year, expressed as metric tonnes of frigate (and bullet) tuna per fishing trip per year. For some months there is lack of catch data, but it is unclear whether this reflects zero catch or lack of data entry, probably the latter. These values may therefore underestimate the true catch of frigate and bullet tuna. However, because of the corresponding lack of effort data, CPUE data may not be heavily biased and should provide a reasonable approximation of stock abundance.

3.3. Results

3.3.1. ***Changes in frigate tuna from catch statistics***

Between 1994 and 2004 catch and catch per unit effort (CPUE) for frigate and bullet tuna (combined) in south-eastern Sri Lanka showed inter-annual fluctuations (Fig 3.2). No clear trend over the decade is evident, except that total catch and CPUE by unclassified gears peaked dramatically in 2002. As indicated, however, catch and effort data for some months are lacking, which probably results in underestimates of total annual catches.

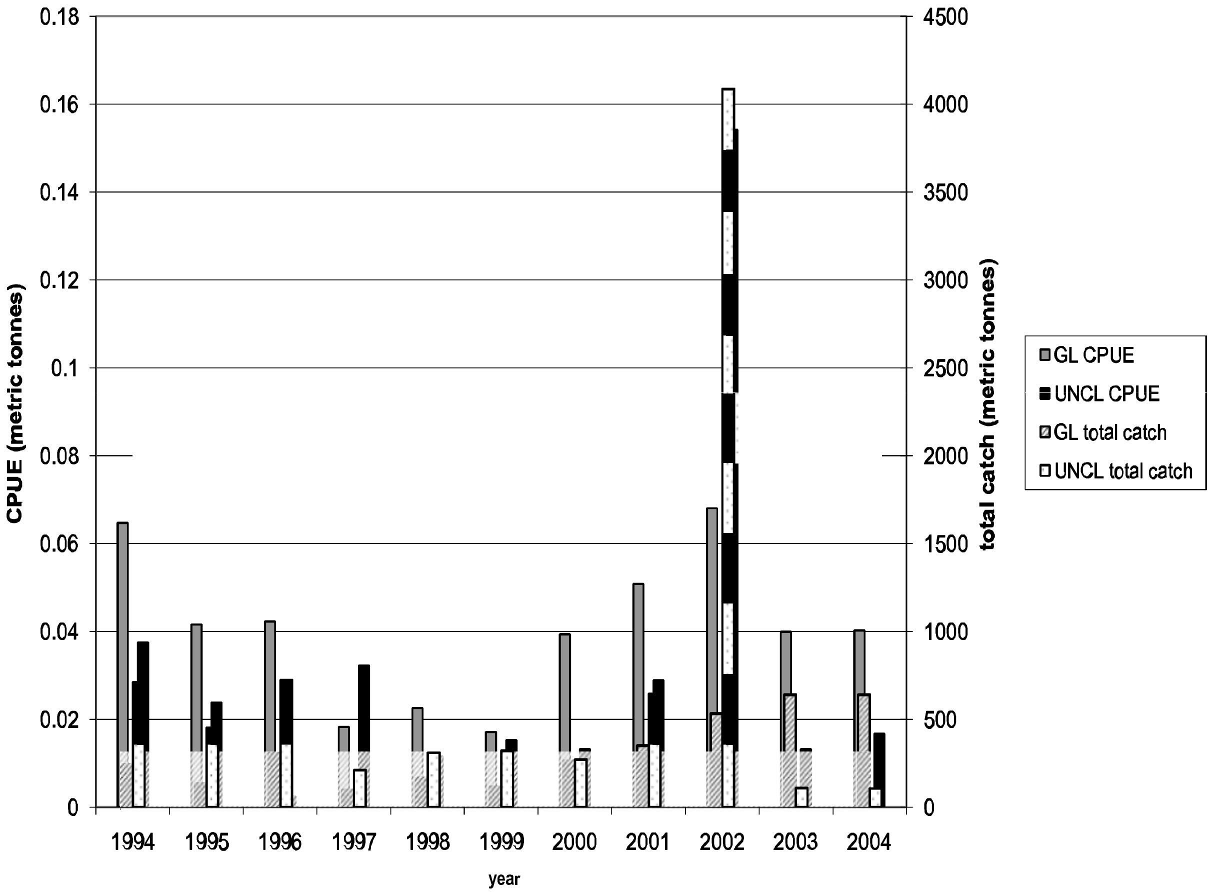


Figure 3.2 Total reported catch data and CPUE for frigate tuna and Bullet tuna (combined), caught by gill net and long-line (GL) and unclassified fishing gears (UNCL) equipment catches for South-eastern Sri Lanka (from Indian Ocean Tuna Commission, 1994-2004). The region encompasses Hambantota and Tangalle, corresponding with the GN divisions where fisher opinions on frigate tuna were evaluated through the questionnaire survey.

Fisher opinions, by age group, on best catches of frigate tuna

The distribution of respondents by age category was 31%, 44% and 25% for age groups 15-30, 31-54 and ≥55 y respectively. Best day's catch and largest frigate tuna ever caught both showed significant positive correlation with age in years, as did the depth and distance offshore associated with best catch and largest specimen landed (Table 3.1). This pattern is mirrored by differences in medians for both best day's catch and largest fish ever caught, which increased significantly with age group (Table 3.2, Fig 3.3). Over 75% of older fishers reported their best catch to be ≥20 kg, whereas only 11% of middle-aged fishers and none of the younger fishers reported catches of this size. Similarly, 70% of fishers aged ≥ 55 y have caught fish ≥ 20 inches, compared to just 19% of fishers aged 30-54 y and 2% of fishers aged 15-30 y.

Table 3.1 Correlations of fisher age and year with best frigate tuna catch, largest size, water depth and distance offshore, using Spearman's rank test, Rs (*p ≤ 0.01), based on questionnaire survey in southern Sri Lanka.

Attribute	R_s with age	R_s with year
Best day's catch (kg)	0.725*	-0.712*
Largest frigate tuna ever caught (inches)	0.754*	-0.763*
Depth associated with best day's catch (m)	-0.429*	0.443*
Distance offshore associated with best day's catch (m)	-0.470*	0.487*

Table 3.2 Medians, inter-quartile ranges (IQR) and results of non-parametric trend test for best catch, distance offshore, water depth and largest fish size by fisher age group, based on questionnaire survey in southern Sri Lanka.

Fisher age group (y)	Median best day's catch size (kg) and IQR	N	Median distance offshore (m) for best day's catch and IQR	N	Median sea depth (m) for best day's catch and IQR	N	Median largest fish ever caught (inches) and IQR	N
15-30	**10 (8-10)**	**37**	**15 (12-20)**	**37**	**14 (11-15)**	**37**	**16 (14-17)**	**37**
31-54	**15 (10-15)**	**53**	**12 (10-14)**	**53**	**10 (10-12)**	**53**	**18 (18-19)**	**53**
55+	**20 (20-20)**	**30**	**10 (10-12)**	**30**	**10 (10-11)**	**30**	**20 (19-20)**	**30**
Z	**7.74**		**-5.12**		**-5.57**		**7.86**	
P *trend*	**<0.001**		**<0.001**		**<0.001**		**<0.001**	

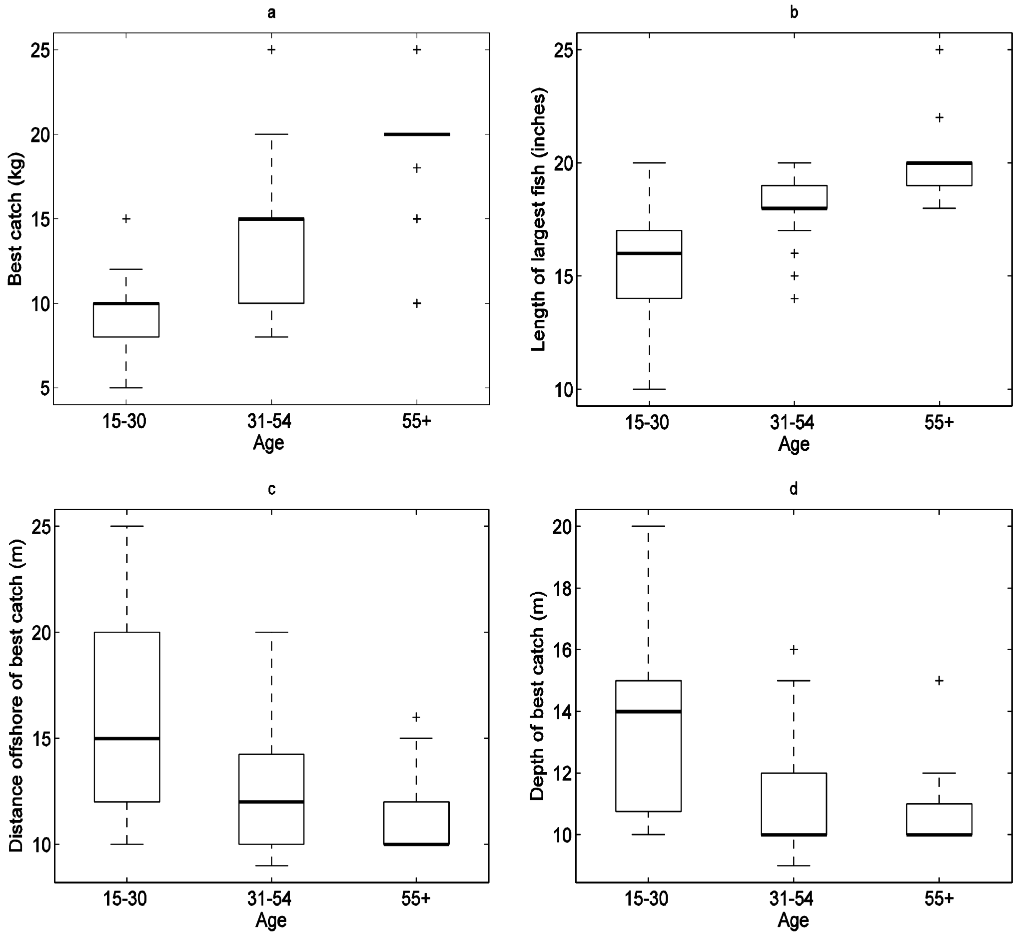


Figure 3.3 Box and whisker plots showing: a) best day's catch, b) length of the largest fish, c) distance offshore associated with best day's catch, d) water depth associated with best day's catch, by fisher age group, based on questionnaire survey in southern Sri Lanka.

Best catch of frigate tuna also showed significant correlation with depth and distance offshore, using data for both fishers' age and age classes (Tables 3.1 and 3.2, Figure 3.3). Older fishers achieved their best catch at 10 m depth, middle-aged fishers at 12 m and young fishers at 15 m depth. Additionally, only 16% of older fishers caught their best catch at ≥15 m from the shore, compared to 62% of younger fishers. Similarly, the median depth associated with greatest frigate tuna catch was greatest for younger fishers at 14 m depth; middle-aged and older fishers both reported a median depth of 10 m. However, differences across all age groups (Table 3.2) are still significant, as the inter-quartile range of middle-aged fishers extends further into deeper waters than that of older fishers: 47% of middle-aged fishers and 27% of older fishers obtained their best catches in depths ≥ 10 m.

The number of fishing sites reported as depleted also varied significantly with age (χ^2 = 38.73, $p \leq 0.01$; Fig 3.4). Older fishers were more likely to name a greater number of sites as depleted. The majority (60%) of fishers ≥55 y reported over 20 sites having a decline in fish catch, compared to 26% of middle-aged fishers and only 8% of younger ones. Furthermore, the majority (>75%) of younger fishers reported that none of the sites they fished had declined, whereas less than 25% of middle-aged fishers and none of the older fishers shared this view.

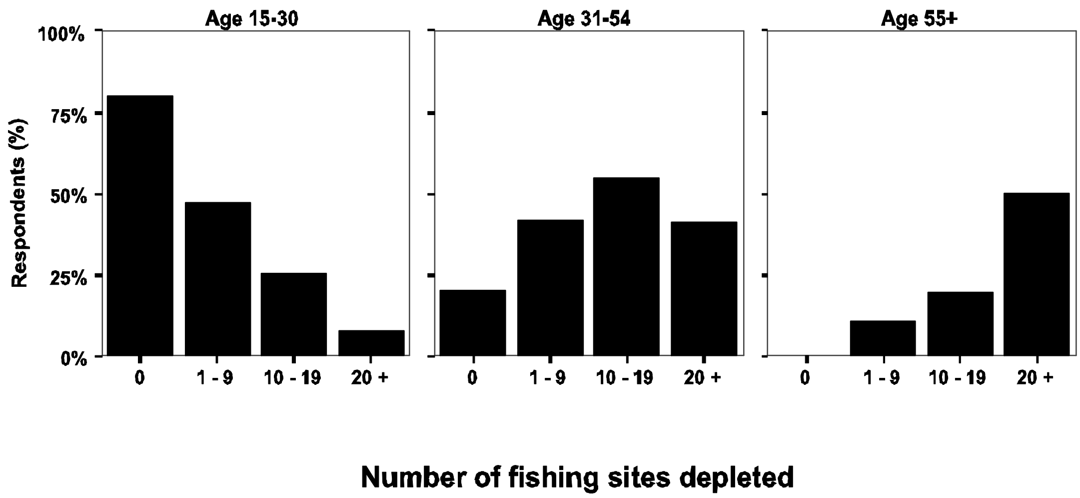


Figure 3.4 The number of sites mentioned by fishers as depleted, by age group, based on questionnaire survey of fishers in southern Sri Lanka.

3.3.2. *Fisher opinions, by year, on best catches of frigate tuna*

Best catch and largest fish ever caught were also significantly correlated with the year this was reported by fishers, as was the depth and distance offshore associated with the best catch (Table 3.1; Fig 3.5). Grouping the data into three year-categories showed a significant trend of decreasing best catch and decreasing size of largest fish amongst younger fishers (Table 3.3). Both depth and distance offshore associated with fishers' best catch were greater during recent years. However, the difference in distance offshore for the periods 1951-1970 and 1971-1990 was not significantly different (Mann-Whitney U test z = 0.211, p = 0.833). Thus an increase is observed only after 1990.

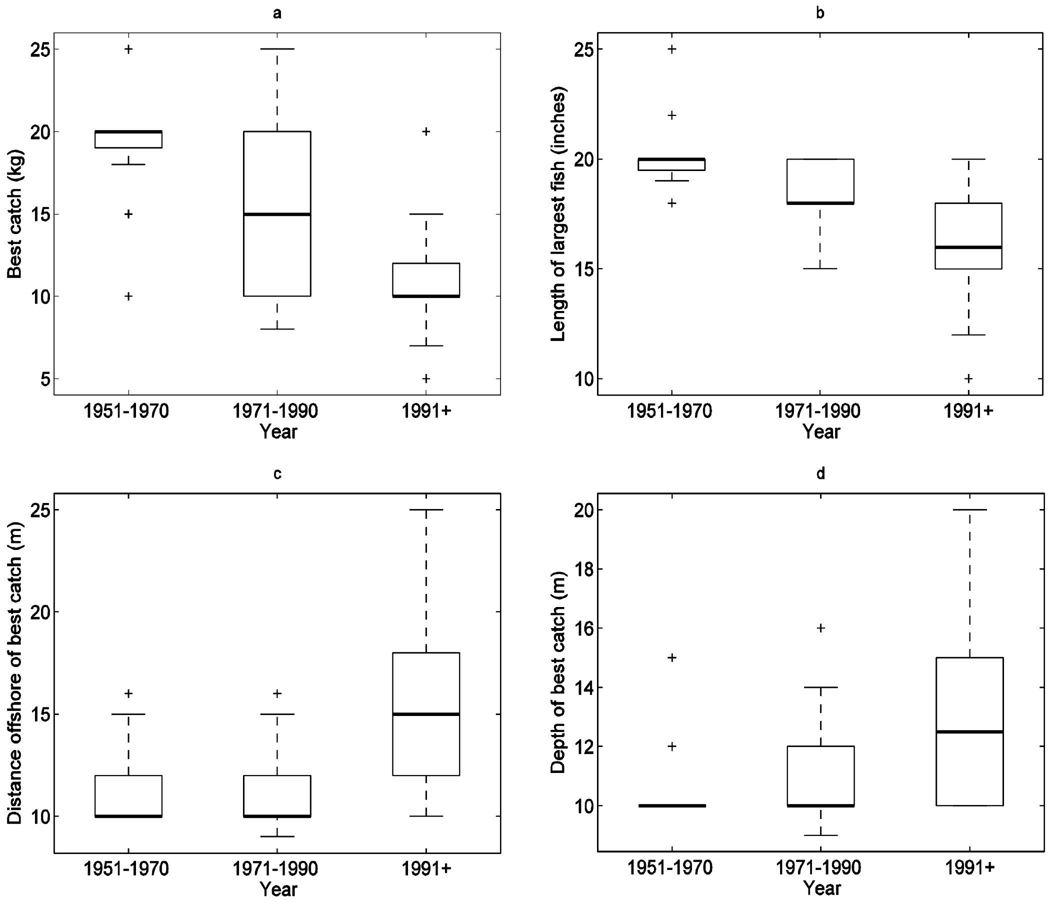


Figure 3.5 Box and whisker plots showing: a) best day's catch, b) length of the largest fish, c) distance offshore associated with best day's catch, d) water depth associated with best day's catch, by year group, based on questionnaire survey of fishers in southern Sri Lanka.

Table 3.3 Medians, inter-quartile ranges (IQR) and results of non-parametric trend test for best catch, distance offshore, water depth and largest fish size by year, based on questionnaire survey in southern Sri Lanka.

Year	Median best day's catch size (kg) and IQR	N	Median distance offshore (m) for best day's catch and IQR	N	Median sea depth (m) for best day's catch and IQR	N	Median largest fish ever caught (inches) and IQR	N
1951-1970	20 (19-20)	20	10 (10-12)	20	10 (10-10)	20	20 (19-20)	21
1971-1990	15 (10-20)	42	10 (10-12)	42	10 (10-12)	42	18 (18-20)	41
Year 1990 +	10 (10-12)	58	15 (12-18)	58	12.5 (12-15)	58	16 (15-18)	58
Z	-6.86		4.86		4.41		-7.26	
P *trend*	<0.001		<0.001		<0.001		<0.001	

3.3.3. ***Changes in frigate tuna catches post-2004 tsunami***

The questionnaire survey also provided an opportunity to seek fishers' views about changes in frigate tuna populations in the aftermath of the tsunami. Besides possible physical or ecological impacts, concern arose over potential unforeseen negative effects of post-tsunami aid, including excessive provision of small fishing craft (Photo 3.1) (Bakus *et al*. 2000; FAO 2005d; FAO 2005a; Pauly 2005; De Silva & Yamao 2007). This dramatically increased pressure on fishery resources, which were already heavily exploited (FGD 2007).

Photo 3.1 Fishing boats on Hambantota coast of Sri Lanka. New boats were given by aid agencies, creating concern that there might be increasing fishing pressure to unsustainable levels.

Of the 120 fishers responding, 100 believed that fish catch had declined since the 2004 tsunami. The majority (72%) attributed the decline to a larger new generation of fishers exceeding numbers of fishers in previous generations. Extra boats provided by aid money and tsunami damage to marine life were reasons indicated by only 15% and 12% of respondents respectively.

Fishers believed that the number of both small and large boats within each of the four GN divisions was significantly greater in 2007 compared to 2004. (Table 3.4). The percentage increase in the median number of boats in each location was 20-36% for small boats and 25-50% for large boats. According to the fishers, Medilla, Mawella and one of the two communities in Gurupokuna all experienced a 50% increase in the number of large boats within their area.

Table 3.4 Comparison of number of boats pre- and post-tsunami for each GN Division, based on questionnaire survey in southern Sri Lanka (*P ≤ 0.01).

GN Division	Median number of small boats 2004	Median number of small boats 2007	Wilcoxon signed-rank test (small boats)	Median number of large boats 2004	Median number of large boats 2007	Wilcoxon signed-rank test (large boats)
Medilla	59	80	-3.765*	30	45	-3.780*
Gurupokuna 1	25	30	-3.753*	15	20	-3.862*
Gurupokuna 2	58.5	80	-3.084*	30	45	-3.126*
Kahadamodara	39	52.5	-4.794*	8	10	-4.894*
Mawella	45	57.5	-5.745*	20	30	-5.387*

3.4. Discussion

Traditional ecological knowledge (TEK), representing experience acquired over hundreds or even thousands of years of direct human contact with the environment, has been identified as valuable in complementing scientific research (Johannes 1998; Johannes *et al.* 2000). Further, case studies show that TEK is often a more cost-effective and less time-consuming means of collecting information on ecological resource pressures and status than more scientific, quantitative approaches (Inglis 1993). In some circumstances it highlights issues which science alone can miss (Berkes 1993; Johannes 1993). The utility of opinion-based surveys has also been highlighted in a recent study in Sri Lanka, which examined ecological and other risk factors influencing the outcome of the 2004 tsunami, in terms of human deaths and housing damage (Venkatachalam *et al.* 2009).

This chapter analyses fisher accounts of frigate tuna, a species commonly caught in Sri Lanka's coastal waters. Changes in populations from reported catch parameters were compared with patterns determined from analysis of available catch statistics.

Results have provided another compelling case of the shifting baseline syndrome, first described more than 10 years ago (Pauly 1995), whereby fishers of different ages have altered perceptions/experiences of their environment. Since then the phenomenon has been documented many times (e.g. Baum & Myers 2004; Saenz-Arroyo *et al.* 2005a; Saenz-Arroyo *et al.* 2005b).Previous research has revealed shifting baselines using similar methodology to document decline of the Gulf grouper (*Mycteroperca jordani*) in the Gulf of California (Saenz-Arroyo *et al.* 2005a; Saenz-Arroyo *et al.* 2005b). It was found that published statistics had grossly underestimated decline in, and conservation status of, the Gulf grouper fishery. Based upon fisher observations between the 1940s and 1970s, these authors show that populations have declined by more than 90%. This qualifies Gulf grouper to be classified as Critically Endangered. Yet the species is actually placed in a lower category of threat, Vulnerable, by the International Union for Conservation of Nature (Hudson & Mace 1996). The reason is that fishery catch statistics do not extend back to a period when the species was highly abundant, and thus severely underestimate decline. This demonstrates the power of imprecise information as a tool for understanding the conservation status of species, which is a requirement for correct management decisions. This study may be the first reported occurrence of the shifting baseline syndrome in Sri Lanka and the findings contribute to growing evidence that coastal fisheries in Sri Lanka are in decline (Stobutzki *et al.* 2006).

The sample size (120 fishers) used for the questionnaire survey is considered to have provided a fair representation of fisher views in four of 19 coastal GN divisions in Tangalle, representing over 5% of the total population of coastal fishers in Tangalle (MFAR 2008). Trends observed were present for all four GN divisions. Logistical constraints precluded more extensive survey. In any questionnaire survey, tradeoffs between number of questions asked, number of interviewees consulted and number of different villages/sites accessed are inevitable.

Despite clear benefits of semi-quantitative and qualitative surveys, care must be taken in collation and use of opinion based knowledge (Oppenheim 1992; Price & Firaq 1996; Venkatachalam *et al.* 2009). Of particular significance is the potential for recall bias, whereby respondent answers are influenced by their memory. In this chapter, fishers along the Hambantota coast often gave a rounded number for their best catch and largest fish size. However, the range of answers within each age group is relatively small, suggesting reasonable or good concordance between respondent answers.

Older fishers reported significantly greater best day's catches and larger fish ever caught than younger fishers. This suggests a decline in frigate tuna populations, particularly as younger generations have access to improved fishing gear (Nevil 2005), and might be expected to obtain better catches. Yet the above findings point to precisely the opposite. Similarly, older fishers obtained their best day's catch in shallower water, and closer inshore, than reported by younger individuals. Undeniably older fishers, having been fishing for longer, would have a greater chance of landing larger and bigger catches than younger ones. But older fishers, potentially, could have obtained their best catches (measured in various ways) in recent years. However, other analyses indicate that this was very unlikely: frigate tuna catch parameters correlated significantly not only with fisher age-group, but also with year (1951-2007). This strongly suggests that harvests were higher in earlier decades of exploitation of the fishery. For example, the largest fish reported between 1951 and 1970 were significantly bigger than those caught from 1989 to 2007; and, similarly, best ever catch was shown to be negatively correlated with year.

The depth and distance offshore at which fishers caught their best catch also increased with age and decreased with year. Although changes in distances and depths are not substantial (medians 10 m to ~ 15 m), the observed pattern suggests that nearshore/coastal populations of frigate tuna may have become increasingly depleted, forcing fishers to travel further and fish deeper waters to obtain good catches. Such consequences of over-fishing have been reported by fishers in other parts of Asia such as Sabah, Malaysia (Teh & Sumaila 2007). It is noted that Sivasubramaniam (1985) records shallower depths of 0-3 m for inshore locations (<25 metres from the shore) for frigate tuna. However, it is possible that the depth of 1.20m given for driftnet fishing should have been 1-20m. If so, the depth range would more closely match that reported in this chapter.

Other evidence of decline in frigate tuna includes the fact that the number of sites associated with a decrease in catch increased significantly with fisher age. This perhaps signifies a rapidly changing ecosystem as well as resource. Younger generations of fishers perceive a more recent 'state' of each fishing site as healthy, and are therefore unaware of its decline in years prior to the period when they began fishing.

Fishery statistics provide a benchmark, against which opinions about catches may be gauged. National catch and CPUE data are available for frigate tuna, but this may well not reflect the status of stocks in southern Sri Lanka. For southern Sri Lanka, only data for frigate tuna and bullet tuna (combined) could be accessed. Despite a peak in CPUE in 2002, the data do not point to any discernible resource decline although, as noted, the data are incomplete and not entirely accurate. The grouping of species in catch statistics can also hide important details (Roberts 2007), easily leading to misinterpretation of the status of a fishery species, especially when catch data extend only over a limited time period.

Earlier stock assessment in southern Sri Lanka concluded not only that fishing has not adversely affected the frigate tuna but also that current exploitation rates could actually be increased by 40% to achieve maximum yield (Dayaratne 1993). However, this author also warned that uncontrolled expansion of the ring net fishery, which began rapid development in Sri Lanka around 1995, could pose problems due to its greater efficiency compared with more traditional technologies. This warning seems particularly relevant for frigate tuna, which comprised 90% of ringnet catch along the southern coast in 1995 (Maldeniya & Dayaratne 1995).

The maximum fork length of frigate tuna (from driftnet records) reported for the Indian Ocean is 51 cm (FAO 2000-2008). Median values for the largest frigate tuna ever caught for all three age-classes in this study (Table 2**)** are lower than this. Additionally, the maximum fork length of frigate tuna (from driftnet records) in Sri Lanka is reported to be 58 cm fork. Yet only two of the 121 fishers questioned recalled catching a fish this large, one in 1953 and the other in 1966. Although it is unclear if fishers in this study were reporting fork lengths, or another length measurement, these results are strongly suggestive of a decline in frigate tuna size as demonstrated above.

Since the 2004 tsunami the majority of fishers believed that catch levels have dropped. Stocks of many fish, including frigate tuna, are reported to have declined post-tsunami, both nationally and in the southern Sri Lanka (De Silva & Yamao 2007; FAO 2007b). Moreover, by May and June 2006 fish catches in Tangalle had still not recovered to pre-tsunami levels (FAO 2007b). Based on fisher accounts, the number of boats within the study area rose significantly after the 2004 tsunami. This is congruent with national figures reporting a total of 4,480 fibre reinforced boats lost to the 2004 tsunami and a total of 7,598 replaced by tsunami aid money (MFAR 2007) and other independent observations (FAO 2005a; De Silva & Yamao 2007). Prior to the 2004 tsunami, there were already reports of excessive fishing boats, even as early as the 1980s (Fonseka 1982).

Despite over-provision of fishing vessels post-tsunami, from documented and fisher accounts, the majority of fishers do not believe this has adversely affected fishing within southern Sri Lanka. Rather, most fishers believe that declines in catches are the result of a larger new generation of fishers agreeing with previous research where fishers were asked about catch decline post-1998 (Perera *et al.* 2001). (It is also a possible, of course, that fishers who had received tsunami aid, in the form of extra boats, were biased and less likely to name this as a cause of fishery depletion.) Between 1989 and 2002 the number of documented fishers in Sri Lanka almost doubled. However, the rise in coastal fish production was only marginal, increasing from 130,000 t to 142,000 t (FAO 2005d). Increased fishing for minimal gain is suggestive of Malthusian over-fishing, whereby small-scale fishers lacking alternative livelihoods over-fish in order to maintain income. This population of fishers then increases, as a result of internal recruitment of fishers' children and migration of people practicing alternative livelihoods into the fisheries sector (Pauly 1990; Pauly 1994).

The full effects of over-provision of fishing boats in Sri Lanka remain unclear. Fishers do not presently hold tsunami aid boats accountable for post-tsunami decline in fisheries. However, perceptions may change, as over-provision of fishing equipment allows a greater population of people to move into the fishery sector, especially if this leads to even less sustainable fishing. Potentially problematic is that many aid agencies in Sri Lanka and other Asian countries provided boats to people who were not actually fishers prior to the 2004 tsunami (Janssen 2005). Some have hypothesized that the rebuilding of fisheries could worsen problems for Asia (CONSRN 2005; Pauly 2005). One possible solution is that alternative livelihoods are found for fishers from areas where coastal fisheries are suffering from excessive fishing (Nevil 2005). However, given the increasing population of fishers, this is unlikely to be an easy task.

Fishing sites in Sri Lanka and throughout Asia are thought to have declined as a result of both over-fishing and environmental degradation (McManus 1997; Stobutzki *et al.* 2006). Destructive fishing methods, such as the use of explosives and bottom-set nets, mining of coral from the sea for lime production, uncontrolled harvesting of reef resources and pollution and sewage have all contributed to the deterioration of the marine environment (Rajasuriya 1997).

The minor fluctuations in frigate (and bullet) tuna catches in southern Sri Lanka, based on patterns from fishery statistics (e.g. Fig 3.2), show no discernible population downturn. Yet there is strong evidence of resource decline using frigate tuna information reported by fishers. Invariably, and perhaps understandably, governments rely mainly on fishery catch statistics to inform decisions about stock size and allowable harvesting levels. As this and other studies (Saenz-Arroyo *et al.* 2005a; Saenz-Arroyo *et al.* 2005b) reveal, though, patterns derived from short time series, i.e. incomplete data, can be wide of the mark. Better decisions are likely if fishery catch data are augmented by records drawing on longer-term information, even if the only source available is reports from fishers.

Although arguably less accurate and precise, fishery management decisions that incorporate accounts of traditional communities and acknowledge the shifting baseline syndrome may often prove more robust than decisions, actions and outcomes reliant on scientific information alone. In the case of frigate tuna in Sri Lanka, analysis of fisher questionnaire data has revealed a marked downturn in the fishery not obvious from catch statistics. In conjunction with more quantitative, scientific approaches, traditional knowledge could be valuable in helping shape future policies by national fishery institutions and improve conservation prospects for seafood species and other natural resources.

4. Risk factors in relation to human deaths and other tsunami (2004) impacts in Sri Lanka: the fishers'-eye view

4.1. Introduction

Artisanal fishers and other subsistence communities can provide valuable information for natural resource management and environmental assessment (Inglis 1993; Johannes 1993; Johannes 1998; Johannes *et al.* 2000). This includes traditional ecological knowledge (Ruddle 1990; Folke 2004), and qualitative information acquired more recently. Both are based on integrated and intuitive understanding of ecosystem services and environmental functioning. Opinion-based knowledge from communities closely connected to their milieu is a relevant complementary information source to more scientific and quantitative data, even in technologically-driven and fast-changing environments (de Kalbermatten 2003).

The present chapter examines damage caused by the 2004 tsunami, based on the opinions of fishers on the Hambantota (south) coast of Sri Lanka. Rural fisher communities have occupied this region and harvested marine resources for many years (see Chapter 3). For example, according to community elders in the Kalameitya area in the Hambantota, coastal fishing was practised by local inhabitants, even in the years before the village temple was built in 1835 (pers. com. M. M. Saman).

The *tsunami* was an event causing devastating effects across the Indian Ocean (Ghobarah *et al*., 2006). In Sri Lanka, 13 of 14 coastal districts were impacted. Death tolls exceeded 30,000 and an additional 502,000 people were displaced. Buildings and infrastructure were devastated (Chapter 2; Appendix 1). The population of Sri Lanka was also affected less directly, through loss of 200,000 livelihoods and disruption to 125,000 jobs (TAFREN, 2007). The impact of the *tsunami* was felt socially economically and psychologically, throughout the whole country. However, the 170,000 commercial and subsistence fishers in Sri Lanka (DCS, 2006b) suffered most, with estimated death tolls between 7,222 (NACA *et al.*, 2005) and 27,000 (UNEP, 2005). Nearly 90% of fishers were affected, through loss of boats, fishing nets and homes (ITDG, 2005; Appendix 1). Fishing industry in the coastal belt collapsed and fish supply throughout Sri Lanka failed, but from disruption to fishing rather than direct impact of the *tsunami* on stocks. Despite mortality to fish, nesting seabirds and some other species groups, *tsunami* damage to ecosystems proved less than expected (Brown, 2006; Wells and Kapos, 2006).

Much has been reported on the ability of natural systems to provide shoreline protection, both in Sri Lanka (Brown 1997, IUCN 2006a) and globally (Mazda et al. 1997, Harada et al. 2002, Bandola and Hussain 2005, Chong 2005, Wells and Kapos 2006). However, given the size of the 2004 tsunami waves (up to 11m; Wijetunge 2006) and heavy damage created, the protective role of ecosystems became equivocal. Early visual assessments made by the population in Sri Lanka and throughout the wider Indian Ocean, reported that extensive stands of mangroves helped buffer the *tsunami* wave and absorb *tsunami* waters, thus alleviating impacts (Bambaradeniya *et al*., 2005a; Brosnan, 2005; Wabnitz *et al.*, 2005). There has also been investment in post-*tsunami* development projects involving restoration of natural systems, including mangroves, in expectation of shoreline protection benefit (IUCN, 2006a).

Intuitive knowledge and community actions can also be helpful at times of natural disasters (Kamara 2005; Sharma *et al.* 2009). This is well documented throughout Asia (Shaw *et al.* 2009) and for rural coastal communities in Sri Lanka, following the Asian tsunami in 2004 (Senaratna, 2006; Senaratna Sellamuttu and Milner-Gulland, 2005). Examples include contribution to damage assessment, social and economic coping strategies used by poor households, and determining priorities for post-tsunami rehabilitation. An opinion-based, semi-quantitative evaluation of tsunami damage and risk factors therefore forms the basis of this chapter. It is seen as complementary to, not an alternative to, scientific assessment involving field investigations and modelling.

The overall aim of this chapter is to assess fishers' perceptions about possible influences on the tsunami outcome, based on 500 questionnaire responses. Specific objectives are to: (1) provide a brief description of overall tsunami impact within the study area; (2) quantify fisher views on the extent to which 13 selected natural environmental and development related risk factors gave protection or increased severity of tsunami impacts, as defined by human deaths and household damage; and (3) determine the influence of fishers' proximity to coast on perceived importance of different risk factors. The chapter also briefly discusses how insights obtained from fishers might assist future coastal management and post-tsunami reconstruction in Sri Lanka.

4.2. Methods

4.2.1. ***The study area***

The Hambantota district along the Southern coast of Sri Lanka (Fig 4.1) was selected for research. Hambantota provides a well characterized area in terms of both ecology, including dry and intermediate climatic zones and socioeconomics. Land use is variable as the district contains both built up/residential areas and natural ecosystems, such as forest and lagoons' (Ratnayake 1989, Senaratna Sellamuttu and Milner-Gulland 2005, Senaratna 2006). Besides fishing, a range of human uses and development activities occur in the area, including tourism, coral mining and irrigation (Senaratna, 2006). Hambantota is further divided by political boundaries into 12 Divisional Secretariats which contain 572 Grama Niladari Divisions (GN divisions). The distribution and magnitude of tsunami damage within Hambantota was variable, with coastal GN divisions experiencing either no, little or severe damage (DCS, 2004b). Although damage to the southern coast was not as severe as on the eastern coast, 2,541 houses in Hambantota were recorded as completely damaged (DCS 2004b; DCS 2006b). Over 16,000 families were displaced and the death toll exceeded 3,000 (Anputhas *et al.* 2005). A range in environmental conditions is important in assessment of different tsunami risk factors.

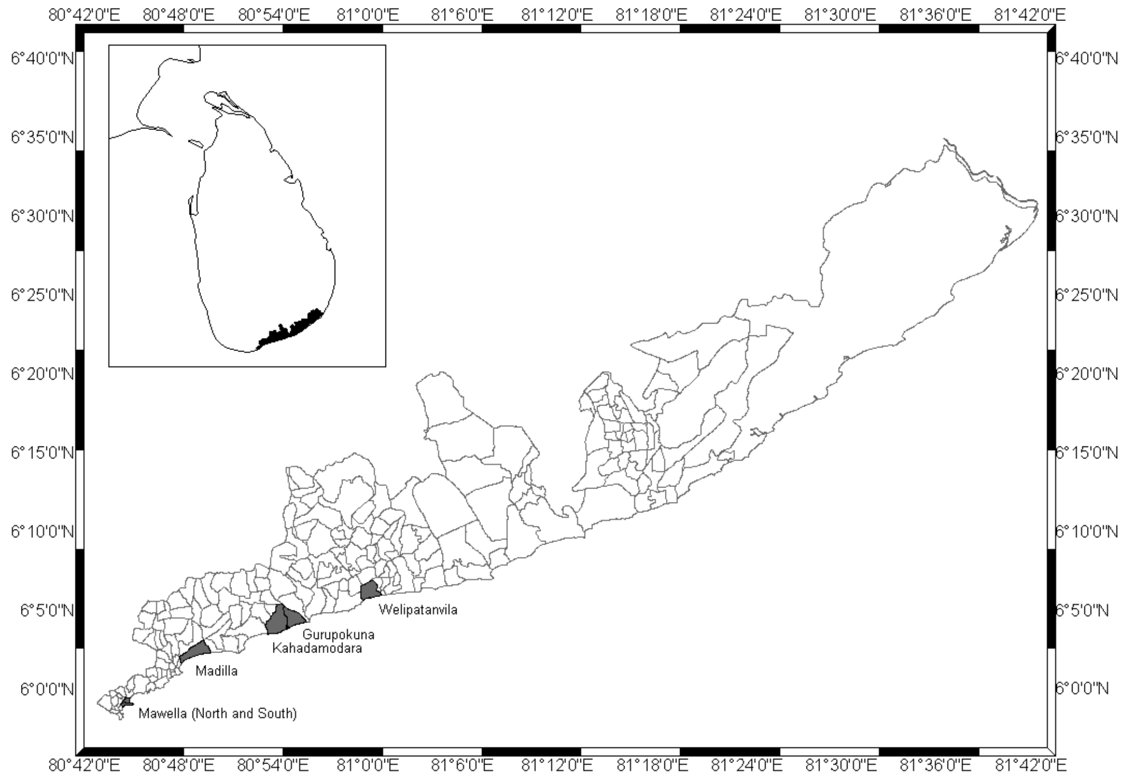


Figure 4.1 Map of Sri Lanka showing Hambantota division, the study area on the south coast (inset) and the 5 GN divisions sampled (from Land Use Planning, Ministry of Land and Land Development, Sri Lanka)

4.2.2. ***Sampling size and strategy***

Win Episcope 2.0 (Blas *et al.* 2000) was used to estimate a sample size which would adequately represent the population of fishers in Sri Lanka. The total population of fishers within Hambantota was not available at the time of this study. The number of people engaged in both fisheries and agriculture (89,394 people in 2004; DCS 2004a; DCS 2006a) was therefore used as an estimate. For statistical purposes, this is a conservative figure, as the actual number of fishers will have been less. Little if any information is available on fishers' opinion regarding tsunami issues. The distribution of opinions of fishers was therefore estimated as 50:50, in order to calculate the largest possible sample size required to accurately reflect population opinions. Sample size was calculated as 475 fishers, with a precision of 4.5% and a confidence interval of 95%. The sample size was finally adjusted for an expected refusal rate of 7.5% based on the experience of interviewers from the Sociology Department, University of Colombo, Sri Lanka. Fishers from 5 GN divisions and 28 villages within Hambantota district were selected for inclusion in the questionnaire survey.

4.2.3. *The questionnaire*

The questionnaire (Appendix 4, *Questionnaire 3*) consisted of two sections: (1) information on the impact of the tsunami on livelihoods, and its direct impact, on the respondent; and (2) perceptions of respondents about the degree to which various natural systems (coral reefs, seagrass, sand dunes, mangroves, rivers and estuaries, coastal shape and beach slope) and infrastructure features (hotels, aquaculture, roads and housing) affected death toll and housing damage. A pilot questionnaire was tested on 10 fishers in Kalametiya and Rekawa on the 10th and 11th March 2007 and, following minor adjustments (e.g. to the scale used to assess the influence of a risk factor) led to development of the final questionnaire (Photo 4.1) (Appendix 4, *Questionnaire 3*).

Photo 4.1 Trialling *Questionnaires 2* and *3* on the Hambantota coast of Sri Lanka (see also Chapter 4).

Interviews were carried out by a team of trained academics and research students from the University of Colombo in accordance with ethical and technical standards (Bunce *et al.,* 2000). Researchers were often accompanied by people with local knowledge. Involvement of local researchers was thought essential to the study, to create a sense of partnership with fishers, gain their confidence and thus help ensure validity of the data collected. This follows the approach adopted during earlier investigations in this area (Senaratna Sellamuttu and Milner-Gulland 2005). Besides the actual questionnaire, interviewers were supplied with a verbal and written brief of the study's research objectives. Over several weeks in April 2007, 515 fishers were approached and interviewed. All fishers approached were male as men comprised 99% of fishers in 2003 (FAO 2005c).

4.2.4. ***Data analysis***

A total of 500 (97%) questionnaires were completed by male respondents engaged in fishing as their primary, secondary or tertiary livelihood. A total of 15 fishers felt unable to complete the questionnaire due to personal time constraints. The distribution of respondents by GN division within Hambantota was 13% for Madilla (9 villages), 20% for Welipantanwila (7 villages), 17% for Gurupokuna (7 villages), 13% for Kahadamodara (2 villages) and 37% for Mawella North and South (3 villages) (Fig 4.1).

Questionnaire data were transferred to a database and analysed using SPSS 14.0 (SPSS Inc., 1989-2005). Respondent opinions on possible tsunami risk factors are displayed as a percentile of the sample group. These were based on one of the following responses: 'decreased impacts', 'no effect', 'increased impacts', 'unsure', 'not present'. Respondents assigning the latter category to a risk factor were excluded from analysis. This left an average of 350 responses for each question. To determine the influence of each individual risk factor, the frequency of responses for 'decreased impacts', 'no effect' and 'increased impacts' were compared by the *chi*-square test of association ('unsure' responses were excluded). If frequencies were significantly different from one another, the modal response class was then used as an index, or proxy, for consensus opinion on that risk factor. When comparing different fisher groups, i.e. coastal/inland responses, the 'unsure' category was included in the analysis. Paired continuous data were compared using a paired samples *t*-test. Graphical comparison of respondents by proximity to coast includes error bars for exact binomial confidence intervals.

4.3. Results

4.3.1. ***Main tsunami impacts in Hambantota region, Sri Lanka***

Of the 500 respondents, 252 were affected by the 2004 tsunami (Q10, Appendix 4). Seventeen or 6.7% of these respondents reported a family death and 3 times this number experienced sickness, disability or injury within their family as a consequence of the 2004 tsunami (Q11, Appendix 4). Loss of household goods (47%) and destruction of business and economic activities (45%) were the impacts most frequently experienced (Table 4.1). The mean pre-tsunami monthly income was SLR 11,356 (US$106), which fell to SLR 9,294 (US$ 86) after the tsunami ($t = 7.69$, $p \leq 0.01$), reflecting a significant impact on earnings (Q7, Q8, Appendix 4). Fisher perception of change in economic status (pre- and post-tsunami) also correlated strongly with income decline ($\chi 2 = 268.94$, $p \leq 0.01$). Before the tsunami, 199 (40%) fishers considered themselves well off, whereas only 81 (16%) did after the tsunami (Q9, Appendix 4).

Table 4.1 Tsunami impacts experienced by 500 fishers interviewed during April 2007 in Hambantota, on south coast of Sri Lanka.

Tsunami impact	No. of respondents	Percentage of sample group
Lost family members	17	6.7
Family members became sick, disabled or injured	58	22.9
House completely destroyed	43	17.0
House partially destroyed	78	30.8
Lost household goods and furniture	120	47.4
Lost cash and jewellery	80	31.6
Lost boats, canoes and nets	97	38.3
Business/economic activities affected or destroyed	113	44.7
Damage to agricultural land	43	17

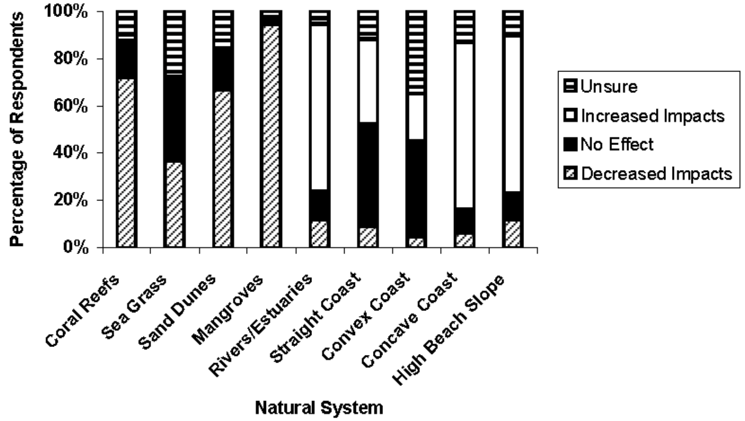
4.3.2. *Fishers' perceptions on risk factors for human death toll and housing damage*

Natural systems

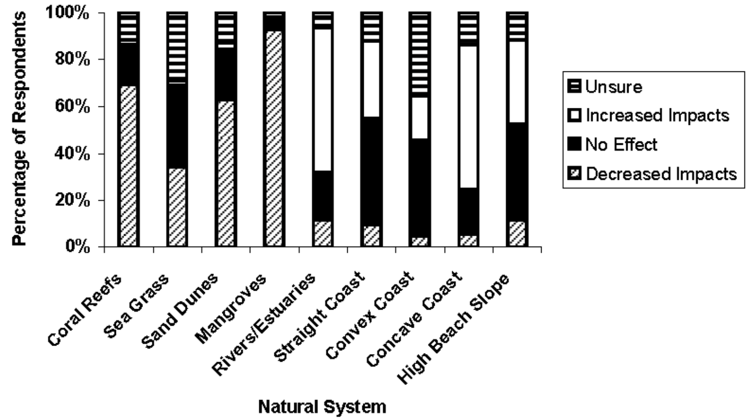
Natural environmental risk factors considered most important in helping decrease human deaths were mangroves, coral reefs and sand dunes (Table 4.2, Fig 4.2) reported by 94%, 72% and 67% of fishers respectively (Fig 4.2a). A similar pattern was evident for housing damage (Fig 4.2b). Natural systems that fishers believed increased the death toll were concave coastline and proximity to rivers/estuaries. These risk factors were considered important by approximately 70% of the respondents (Fig 4.2a). Concave coastlines and river/estuary presence were also identified as risk factors contributing to increased housing damage. People's opinions of seagrass and other natural environmental features was less clear (Fig 4.2a, b).

Table 4.2 Chi square values to determine if there was a significant difference between respondent opinions ('decreased impact', 'increased impact', 'no effect', after omitting 'unsure' responses) on each risk factor examined (*significance at p≤0.01 level and ** significance at p≤ 0.001). Significance allowed reporting of the consensus opinion, determined from modal response class (see Fig 4.2).

	Impact indicator	
Risk factor	*Deaths*	*Housing*
Natural system	χ^2 **value**	χ^2 **value**
Coral Reefs	536.97^{**}	499.22^{**}
Seagrass	186.97^{**}	180.46^{**}
Sand Dunes	441.22^{**}	371.87^{**}
Mangroves	782.45^{**}	744.72^{**}
Rivers/Estuaries	465.72^{**}	288.44^{**}
Straight Coast	126.86^{**}	132.81^{**}
Convex Coast	115.89^{**}	123.57^{**}
Concave Coast	11.16^{*}	276.23^{**}
High Beach Slope	410.43^{**}	99.67^{**}
Development or infrastructure		
Hotels	51.22^{**}	182.05^{**}
Fish/Shrimp Farms	19.40^{**}	23.42^{**}
Roads	55.00^{**}	141.05^{**}
Housing	95.22^{**}	43.00^{**}



a



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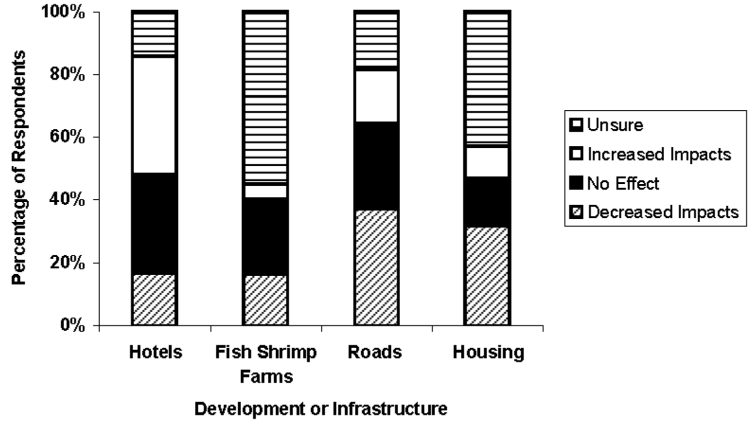

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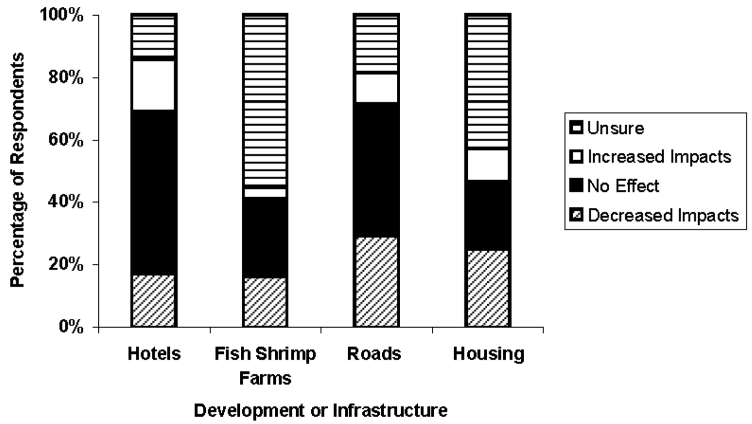

d

Figure 4.2 Fishers' opinions on the role of different risk factors (presence of natural systems and development features/infrastructures) in alleviating or exacerbating tsunami impact in Hambantota, Sri Lanka: a) natural systems Vs death toll, b) natural systems Vs housing damage, c) development features Vs death toll d) development features Vs housing damage.

Development features and infrastructure

Fishers believed that development features and infrastructures influenced tsunami impacts. Over 30% of fishers believed roads and housing decreased deaths (Fig 4.2c). Housing also decreased household damage (25% of responses) (Fig 4.2d), i.e. contents/furniture. In contrast, nearly 40% of fishers believed that hotels exacerbated the death toll (Fig 4.2c). In the case of fish and shrimp farms, these are uncommon development features in Hambantota, and only about 20% of fishers gave an opinion. Of these, 55% reported they were unsure of the influence fish and shrimp farms had on tsunami impacts (Figs 4.2c, d).

4.3.3. ***Influence of fishers proximity to coast***

Fifty-nine of the respondents lived within 100 m of the coast at the time of the tsunami. Of these, 93% were affected by the tsunami compared to 45% of people living further inland. Opinions of the two groups on the influence of rivers/estuaries, road systems, housing and hotels differed significantly (Fig 4.3). In every case, a larger proportion of fishers living close to the coast believed these risk factors had helped reduce human deaths than those further inland. Correspondingly, and as a cross-check on response consistency, more respondents further inland believed these risk factors increased the death toll in comparison with those near the coast. Response patterns for these risk factors in relation to house damage are very similar (Fig 4.4). In the case of other risk factors, either there was no significant difference between responses from fishers near the coast and those further inland, or sample size was small.

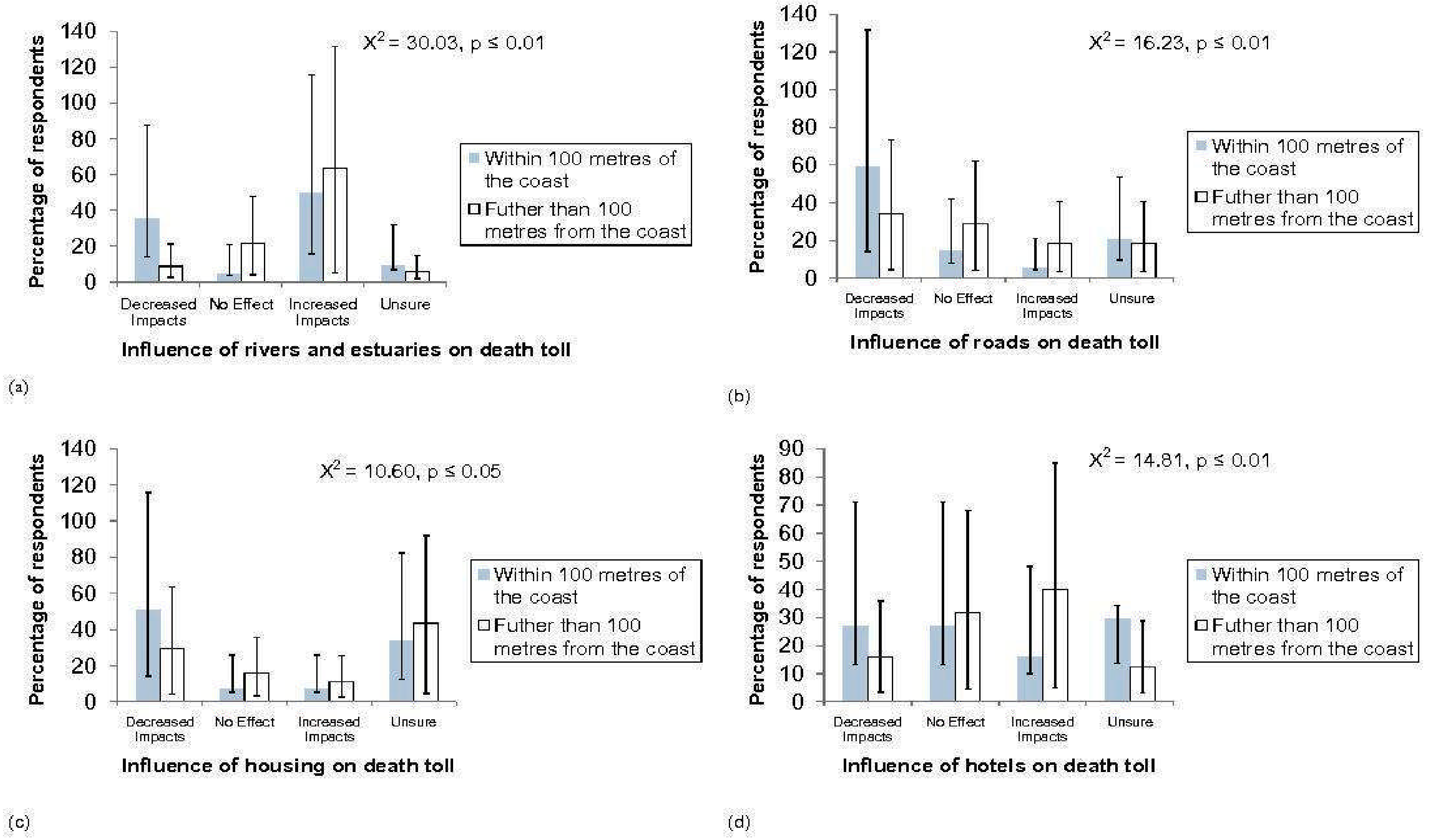

Figure 4.3 Opinions of fishers living within 100 m of the coast vs those living further inland on the role of rivers and estuaries, roads, housing and hotels in alleviating or exacerbating tsunami death toll in Hambantota, Sri Lanka: a) Rivers and Estuaries b) Road Systems c) Housing d) Hotels.

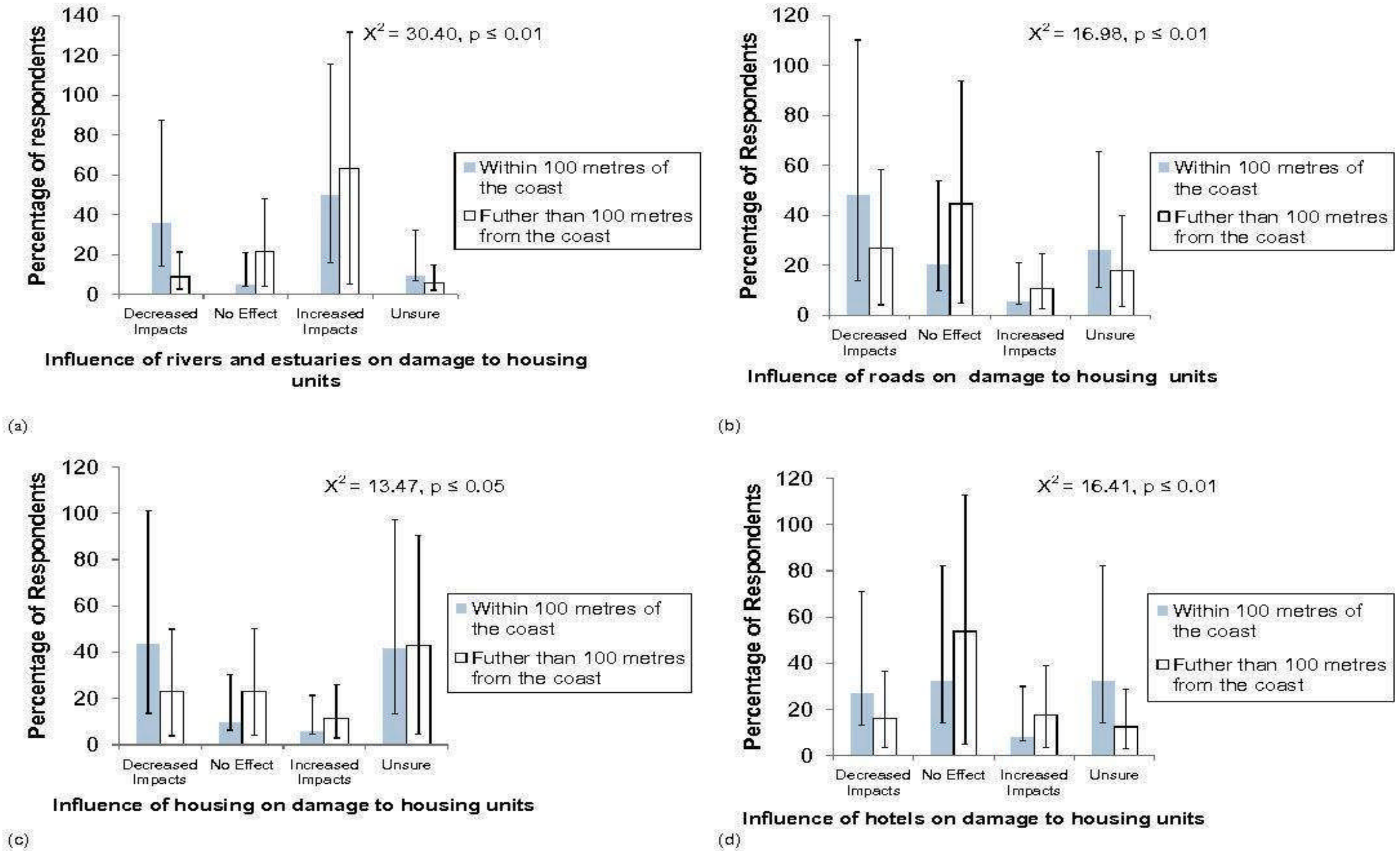

Figure 4.4 Opinion of fishers' living within 100m of the coast vs those living further inland on the role of rivers and estuaries, roads, housing and hotels in alleviating or exacerbating tsunami housing damage in Hambantota, Sri Lanka: a) Rivers and Estuaries b) Road Systems c) Housing d) Hotels.

4.4. Discussion

This chapter attempted to evaluate tsunami impacts and potential risk factors in one area of Sri Lanka, through a questionnaire survey of fishers. Environmental insights obtained from local expertise, as noted, can be a valuable supplement to more ‘scientific’ surveys (Pauly 1995; Price & Firaq 1996; Saenz-Arroyo *et al.* 2005a; Saenz-Arroyo *et al.* 2005b). In fact, a study on fisher opinions has revealed that fisheries and conservation science seriously underestimated the decline in Gulf grouper in Mexico (Saenz-Arroyo *et al.*, 2005a). Other marine resource assessment models have also been wide of the mark (Roberts, 1997). However, use of opinion-based knowledge can also be problematic. For example, opinions may not have the accuracy or precision of scientific measurements and limiting bias is an issue that cannot be dismissed lightly (Oppenheim, 1992; Price and Firaq, 1996). As indicated in this chapter and existing research, the study area selected (Hambantota) provided a reasonable cross-section of both biophysical conditions and communities affected by the tsunami on Sri Lanka’s southern coast (Senaratna Sellamuttu and Milner-Gulland, 2005; Senaratna, 2006).

Although sample size was calculated, and seems adequate (500 questionnaire responses), spatial coverage of Hambantota was rather limited. This chapter investigated four of the 48 coastal GN divisions, plus another inland GN division. Logistical constraints precluded more extensive survey. Similarly, a more comprehensive study would be needed to encompass all socioeconomic classes within coastal regions of Sri Lanka, even on the south coast. For this reason, individuals for whom fishing was the sole or major livelihood were deliberately targeted. This prevented the possibility of occupation acting as a confounding factor.

Besides the problem of ensuring representativeness, other forms of bias can accompany an opinion survey such as this. In the aftermath of the 2004 tsunami, for example, many visitors to Sri Lankan fishing villages were there to administer aid (Risvoll 2006). Consequently, respondents could have over-estimated damage in this survey in the mistaken belief that this might lead to reward. However, this chapter focussed on potential risk factors rather than damage, hence, any overstatement of impacts is not seen as a critical issue here. Fisher opinions may also have been influenced by post-tsunami environmental public awareness programmes and coastal restoration projects implemented by IUCN and other aid agencies, as part of disaster mitigation and reconstruction (Photo 4.2). This has included mangrove replanting (IUCN, 2006b; Ranasinghe and Kallesoe, 2006). Hence, the possibility of conservation materials and activities influencing fishers' perceptions, and their responses, about the role of natural systems cannot be excluded.

Photo 4.2 Conservation organizations developed extensive public awareness programmes in the aftermath of the 2004 tsunami, offering advice on likely risk factors in Sri Lanka. These are examined in Chapters 4, 5 and 6).

Despite undeniable shortcomings of rapid/semi-quantitative appraisal techniques, their benefits can often outweigh any limitations (e.g. Price 1990; Price & Firaq 1996; Price 2004; Saenz-Arroyo *et al.* 2005a; Saenz-Arroyo *et al.* 2005b). Advantages include possibilities for good spatial coverage, from a large number of observations and/or large sample size, over relatively short time scales; a broad range of environmental or other factors that can be examined; and potential for at least good qualitative understanding of environmental disturbance, bypassing need for more costly scientific survey. Set against these advantages, rapid assessment data are necessarily of lower resolution and more imprecise than more quantitative approaches. Similarly, parametric statistical tests are often possible on data from detailed scientific investigations whereas only non-parametric tests, which are less powerful, are normally permissible for rapid assessment data. Assessment inevitably requires compromise, and a balance between high- and low-resolution methods generally yields the greatest insights into complex environmental issues. Given the finite resources available, questionnaire data on fishers' views provided a valuable perspective on tsunami risk factors, as well as a different but complementary approach to modelling and ecological surveys.

Although this chapter focused on impacts 2.5 years after the tsunami, the extent of its impact was still evident within the livelihoods of fishers. Income levels were lower than those reported before the tsunami and fishers considered their economic status to have declined after it. This finding is congruent with the latest Needs Assessment Survey for Income Recovery where 81% of 1039 respondents stated that the income they earned in 2006 was less than that pre-tsunami (ILO & RADA 2007).

Mangroves, coral reefs and sand dunes were thought by fishers to decrease the impact on human deaths and housing damage. Their opinion on the protective role invoked for seagrass beds is less marked. The findings for coral reefs and mangroves support some early scientific studies on the southern coast of Sri Lanka (Fernando and McCulley, 2005; Dahdouh-Guebas *et al.,* 2005) and elsewhere (Kathiresan and Rajendran, 2005). However, modelling (carried out over 56 sites), using inundation distance as an indirect proxy for tsunami impact, concluded that mangroves and corals reefs had no significant effect (Chatenoux and Peduzzi, 2005). Although this may be true for extent of wave intrusion, it is possible that natural systems played a role in the force at which waves reached this point and the actual destruction caused. The divided scientific opinion about the role of coral reefs is mirrored by the difference in views amongst fishers.

High beach slope was identified as a factor which increased tsunami death toll. Beach slope is a complex risk factor and one invoked as directly influencing tsunami inundation (Abdul Rasheed *et al.* 2006; Kurian *et al.* 2006). This risk factor may have been misunderstood by interviewees, with possible confusion between beach angle (the intended meaning) and beach height/elevation. Not surprisingly, models have identified elevation and bathymetry as important risk factors (Chatenoux and

Peduzzi, 2005). Arguably, this should have been an explicit risk factor in the questionnaire survey. However, the influence of factors such as bathymetry is highly complex and not an issue easily, if at all, discernible by eye witness accounts.

The presence of concave coastlines and rivers/estuaries were implicated by fishers as a whole as something which increased deaths and housing damage from the tsunami. Concave coastlines cause convergence of waves, channelling tsunami waters towards the shore (Bambaradeniya *et al.* 2005a; Jayakumar *et al.* 2005; Murthy *et al.* 2006). Residents living 3.5 km upstream from the Yan Oya River in Sri Lanka reported the river rising as high as 4 m at the time of the tsunami (Yasuda *et al*. 2006). This allowed intrusion of the tsunami further inland (Yasuda *et al.* 2006), thus increasing the scale of damage there. Fisher responses would seem in accordance with this observation, in that a significantly greater proportion of individuals living within 100 m of the coast believed that rivers and estuaries afforded protection compared with those living further inland.

Development related factors also influenced tsunami impacts. Fishers, collectively, felt that hotels increased deaths. Given that hotels are large physical structures and may have blocked/prevented tsunami intrusion, this result is unexpected. The fishers did, however, implicate housing as a protective factor against death toll. Fishers also believed that roads helped reduce the tsunami death toll, perhaps, although not stated by them, by providing an escape route from the deluge of water.

Determining factors which provided protection from the 2004 *tsunami* is complex. Not even measurement of impact is straightforward, as it can be determined in different ways. For example, inundation distance as used in models is relatively easy to measure (from satellite imagery and field study), and provides relatively high resolution data. As implied, however, it is probably an incomplete indicator of tsunami damage. Deaths and household damage would seem more direct and intuitive measures of tsunami damage, but here the accuracy of statistics cannot be guaranteed. Additionally, some of the response patterns by fishers to some of the risk factors (e.g. hotels) are open to different interpretations and must remain speculative. There are many potential risk factors, all can be measured, and all such measurements have their own value according to the context. No single measure or indicator of tsunami damage can be ideal.

This chapter's findings demonstrate a need to clarify the influence of ecosystems such as mangroves in defence against hazardous events such as *tsunamis*. Support for their protective role against *tsunamis*, as suggested by this chapter and several field investigations, might seem at odds with the conclusions of recent models. As noted, however, inundation distance is the proxy for impact used in modelling, whereas both this questionnaire study and field investigations utilised more direct measures, such as human deaths and housing damage. Therefore studies often differ in both methodology and the means by which they measure *tsunami* impact. The results of this chapter are certainly not taken to imply that perceptions have more validity than scientific results. But there is ample evidence that other types of knowledge can usefully complement scientific views. Models presented in Chapter 6 provide further information on the relative influence of mangroves, other natural systems and development factors as risk factors.

Besides their equivocal role in tsunami protection, however, Sri Lankan mangroves provide many clear-cut ecosystem services (Hogarth, 1999; Ranasinghe and Kallesoe, 2006). Ongoing mangrove loss or degradation, at levels that have occurred in Sri Lanka over recent decades, could be highly risky for environmental conservation and impede certain coastal future development options (but, arguably, create others). The conservation importance of mangroves is certainly implicit in national environmental and international legislation (e.g. Convention on Biological Diversity & Ramsar Convention to protect wetlands), to which Sri Lanka is party.

Sri Lanka has recently embarked on post-tsunami reconstruction. This might provide an opportunity for more integrated coastal management, although competition for space and finite resources is likely to remain a critical issue. Although the validity of the views of Sri Lankan fishers about tsunami risk factors requires clarification, this community could have a role in helping scientists, economists and professional decision-makers shape national coastal policies. In fact, a rural coastal community on Sri Lanka's Hambantota coast has already made 10 recommendations on how to best prepare for future disasters (Seneratna, 2006).

Amongst these are: planting of coastal vegetation for protection; stabilising the coastline using boulders; develop an early warning system; build houses near the coast on stilts; educate the community about tsunamis and other natural disaster. In any coastal setting and hazardous area, transfer of knowledge is important, worldwide and locally (UNESCO 1993), both from science to local communities, and *vice-versa*.

5. Characterisation of ecological and socioeconomic risk factors and impact indicators for use in tsunami risk model

5.1. Introduction

Understanding which factors accentuated and exacerbated the outcome of the 2004 tsunami in Sri Lanka requires identification and quantification of risk factors and the selection of appropriate impact indicators. In order to accurately identify tsunami risk factors within Hambantota, collation and extraction of specific information on the region was required. Very few publically available sources of information identify land uses and accurately define their spatial location. Most existing reports with spatial reference are limited to one ecosystem or land classification (Spalding *et al.* 1997; Spalding *et al.* 2001; Green & Short 2007).

A need was identified to create a geographic information system (GIS) and database specific to the southern (Hambantota) coast of Sri Lanka. A suitable GIS would need to encompass information from a number of sources. Information collated and utilised can be classified under three fundamental areas; (i) demographics and tsunami impacts, (ii) ecosystems and land uses, (iii) geomorphic and physical attributes. This chapter is essentially methodological and the overall aims are i) to identify and characterize risk factors and impact indicators potentially relevant to the understanding of 2004 tsunami impact on the southern coast of Sri Lanka; and ii), to quantify these risk factors and impact indicators using GIS techniques.

5.2. Methods

5.2.1. ***Spatial scales for assessing features of Hambantota***

In order to more accurately assess the environment within Hambantota, the divisional secretariat was divided into smaller areas and assessed on two scales. Firstly, by GN divisions, which are the smallest administrative districts within Sri Lanka, and then by smaller subdivisions constructed every 300 m along the coastline.

GN divisions were defined by maps supplied by the Land Use and Planning Department, Sri Lanka. Smaller subunits were created through transformation of the GN map using the ‘Feature to Line’ tool within the ‘Data Management Toobox’ in ArcView, thus creating polylines representing both GN and coastal boundaries. Polylines representing the coastal boundary were divided into intervals of approximately 300 m using the ‘split polyline’ tool in ET Geo Wizards (Tchoukanski 2009). A perpendicular line was then drawn from the end of each 300 m polyline segment to the internal GN boundary, to create 300 m subdivisions along the coast. This resulted in Hambantota being split into 335 subunits.

5.2.2. ***Demographics and other tsunami impact indicators***

Several demographic and ecological impacts indicators were used as proxies for tsunami damage. Data on demographics in Hambantota were extracted from the annual reports and databases compiled by the Department of Census and Statistics (DCS 2001; DCS 2004b; DCS 2004a; DCS 2006b).

Data on total population, total number of housing units, the number of damaged housing units and death toll associated with damaged housing units were extracted manually from DCS databases for each coastal GN division. Divisions were ranked based on populations and housing density to assess which areas were most highly and sparsely populated.

Data on partially and fully damaged housing units were added together to create a combined index. These data were used to calculate the proportion of the total number of houses in the GN division that were damaged. Similarly death toll as a proportion of the division population was calculated. Data were later entered into ArcView with appropriate coding to allow geographical display.

Tsunami inundation, in terms of maximal distance, and area, were calculated from maps provided by the Coast Conservation Department, Ministry of Fisheries. Maps were received as geo-referenced tiff images. These images were imported into ArcMap (ESRI Inc. 1999-2006) and assigned a geographic projection.

Hence, in total, data on four different impact indicators were compiled for use as output variables: human deaths, housing damage, inundation distance and inundation area.

5.2.3. ***Tsunami risk factors: ecosystems and land uses in Hambantota***

GN divisions

All land uses within the research area were extracted from maps provided by the CCD, as described for the extraction of tsunami inundation measures. Land uses included both development features, such as, residential and built-up areas and natural systems including forests, marsh land, salt pans, sand dunes and lagoons.

To facilitate creation of a GIS for the 39 coastal GN divisions, areas of different habitat/function within the boundaries of each GN were delineated using the sketch tool in ArcMap. This constructed a total of 360 polygons. Polygon areas were then calculated using the ArcMap field calculator and entered into a database. In addition to quantifying habitats and land uses within GN division boundaries, areas were also quantified within the bounds of tsunami inundation. This area included a 15m zone outside the actual tsunami inundation area to encompass land uses which were present at the point at which inundation ceased.

Additionally, the presence or absence of each land use/ecosystem was also determined for a 15 m ‘buffer zone’ which followed the coastline. This was done to determine which land uses/ ecosystems were prominent at the coastal edge where the tsunami first intruded. This was achieved by sketching a polyline representing the coast and, using the editor toolbar, to construct a 15 m buffer zone. Presence and absence of each land use and ecosystem was assessed visually.

Maps provided by the CCD did not identify mangroves, seagrasses and coral reefs separately. The presence or absence of these ecosystems within GN divisions and subunits was quantified from scientific literature (Sheppard *et al.* 1996-1997; Spalding *et al.* 1997; Spalding *et al.* 2001; Green & Short 2007). Presence of mangroves, seagrasses and coral reefs were identified and calculated visually, on both electronic and paper maps.

All information sources on ecosystem or land-use occurrence and distribution were also checked against satellite imagery on Google Earth (Google 2009) where images are within the range of 1-3 years old (Google 2010).

GN division subunits

The GIS database constructed to calculate areas of habitats within each GN division was split using ET Geo Wizards (Tchoukanski 2009). This allowed areas of habitat and land uses to be calculated for each of the subunits using methods described for GN divisions (above). Each of the 5,773 ecosystem/land use polygons was then manually coded with a number identifying them to a distinct subunit along the coast.

5.2.4. ***Physical attributes of Hambantota***

Bathymetry

Bathymetry data was extracted from the General Bathymetric Chart of the Oceans (GEBCO) produced by the British Oceanographic Data Centre (IOC *et al.* 2003). The gridded bathymetry data was converted to an ArcMap compatible ESRI ASCII grid using Generic Mapping Tools (GMT) (http://gmt.soest.hawaii.edu/). Conversion tools were then utilised to transform the ESRI ASCII grid into a raster image.

Two hundred metre long transects in the direction of the tsunami epicentre were constructed every 300 m along the coast, starting at the midpoint of the first subunit. Transects were then converted into a series of 3D points. Three dimensional data in the form of (x,y,z) coordinates for each transect were extracted and exported to MatLab (The Mathworks Inc. 1984-2006). Matlab was utilised for plotting the transects in 3D space, allowing identification of distinct slopes along each transect. Both the gradients and lengths of slopes identified were then calculated and entered into database. Slope lengths and gradients were averaged from relevant subunits to obtain a value for GN divisions.

Topography

Coastal topography of Hambantota was quantified for each GN division or subunit from the SRTM (90m) Digital Elevation Model downloaded from the CGIAR Consortium for Spatial Information (Jarvis *et al.* 2008). The 'zonal statistics' function within the Spatial Analyst extension of ArcView returned the mean, minimum and maximum height above sea level for each zone, where zones were defined as the subunit/GN boundary.

Coastal shape

Coastal shape is believed to have been an important tsunami risk factor; concave shorelines have the effect of funnelling or concentrating the tsunami wave, while convex shorelines do the opposite, i.e. deflect the tsunami wave (Venkatachalam et al. 2009). Coastal shape was quantified for 600 m and 6 km coastal stretches using maps showing the Sri Lankan coastline (LUPPD 2007). This was achieved by taking a midpoint for each subunit on the coastline and then two points on either side of this point either 300 m or 3 km away. These points were used to construct right-angle triangles and subsequently calculate the angle of the coast between the midpoint and each of the flanking points. These angles were subsequently subtracted from one another to give a measure of convexity or concavity (Fig. 5.1). For GN divisions, the midpoint of each GN division was taken and the midpoints of adjacent divisions. These coordinates were then treated in the same manner as those extracted for subunits. Once angles were subtracted from one another, a return of 0 corresponded to a straight coast, whereas negative values represent convex coastlines and positive represented concave coastlines. For the purposes of modelling (Chapter 6), angles between -15º and 15º were classified as approximately straight, <-15º as convex and >15º as concave.

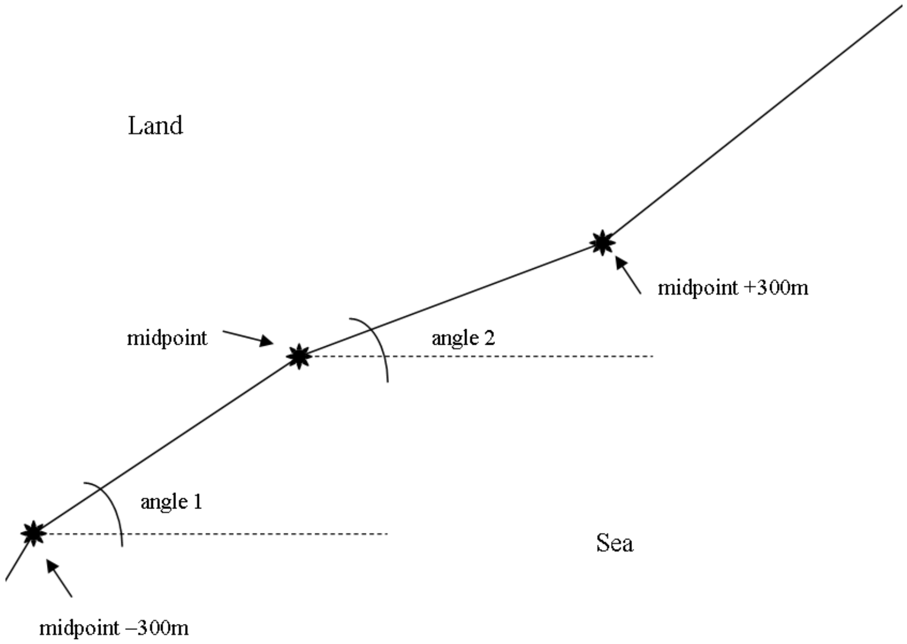

Figure 5.1 An example of a portion of the coastline for which concavity/convexity was estimated. Angle 2 was subtracted from angle 1 to give a measure of concavity/convexity of the coastline over a 600m portion of the coastline. The same principles were applied for large 3km /GN division coastline stretches.

Coastal angle

For each GN division or subunit the coastal angle was approximated and entered into models. Coast angle is believed to reflect the strike angle of the 2004 tsunami. This was achieved by artificially constructing a line between midpoints of the two adjacent GN divisions/subunits and calculating its angle in relation to North (e.g. where a vertical coast running from South to North would return a 0º value and a horizontal coast running from West to East would return a 90º angle).

5.3. Results

5.3.1. ***Hambantota demographics***

GN divisions

Identifying GN divisions with greatest human habitation gave similar results whether the population or the number of housing units was assessed. Many of the same GN divisions therefore appear in the 5 highest and 5 lowest ranking GN divisions for both of these indices (Table 5.1). However, Pallikkudawa, which has the highest population, does not appear in the list of five divisions with the greatest number of housing units.

Table 5.1 The 5 GN divisions with the greatest and lowest level of human habitation based on population and the number of housing units.

5 GN divisions with largest human habitation			
GN	Population	GN	Number of Housing Units
Pallikkuduwa	10110	Hambantota West	2078
Hambantota West	8757	Kirinda	1200
Kirinda	3479	Sisilasgama	711
Sisilasgama	2864	Mirijjavila	589
Hambantota East	2456	Hambantota East	584
5 GN divisions with smallest human habitation			
GN	Population	GN	Number of Housing Units
Gurupokuna	456	Gurupokuna	106
Mawella North	462	Mawella North	109
Medegama	528	Moraketi Ara East	141
Welipatanvila	570	Welipatanvila	157
Moraketi Ara East	581	Medegama	171

Population and death toll (as a proportion of the population) do not appear to follow the same pattern, despite some overlap (Fig 5.2). There is no significant association between population size and raw death toll numbers or housing damage and housing density (Table 5.2, Fig 5.3).

Table 5.2 Matrix showing Spearman's Rank Correlation coefficients between demographics and tsunami outcome statistics for GN divisions.

Statistics	Population	Housing Density	Death Toll	Housing Damage	Inundation Distance	Proportion of Area Inundated
Population	-	0.83*	0.14	0.18	0.07	0.02
Housing Density	-	-	0.13	0.14	0.22	0.22
Death Toll	-	-	-	0.91*	0.13	0.08
Housing Damage	-	-	-	-	0.27	-0.02
Inundation Distance	-	-	-	-	-	0.28
Inundation Area	-	-	-	-	-	-

* indicates significance at the 0.05 level.

Human indicators of tsunami impact (i.e. death toll and housing damage) followed a similar geographical pattern to one another (Fig 5.2 & 5.3), where GN divisions experiencing a high death toll also had an increased level of damage to housing units. These two measures are correlated for the 39 coastal GN divisions (Table 5.2). The physical indicators of tsunami impact, inundation distance and the proportion of land inundated were not correlated with one another at the GN division level and portray a different geographical pattern (Fig 5.4). Additionally, these physical indicators of impact were not correlated with socioeconomic indicators of impact (Table 5.2).

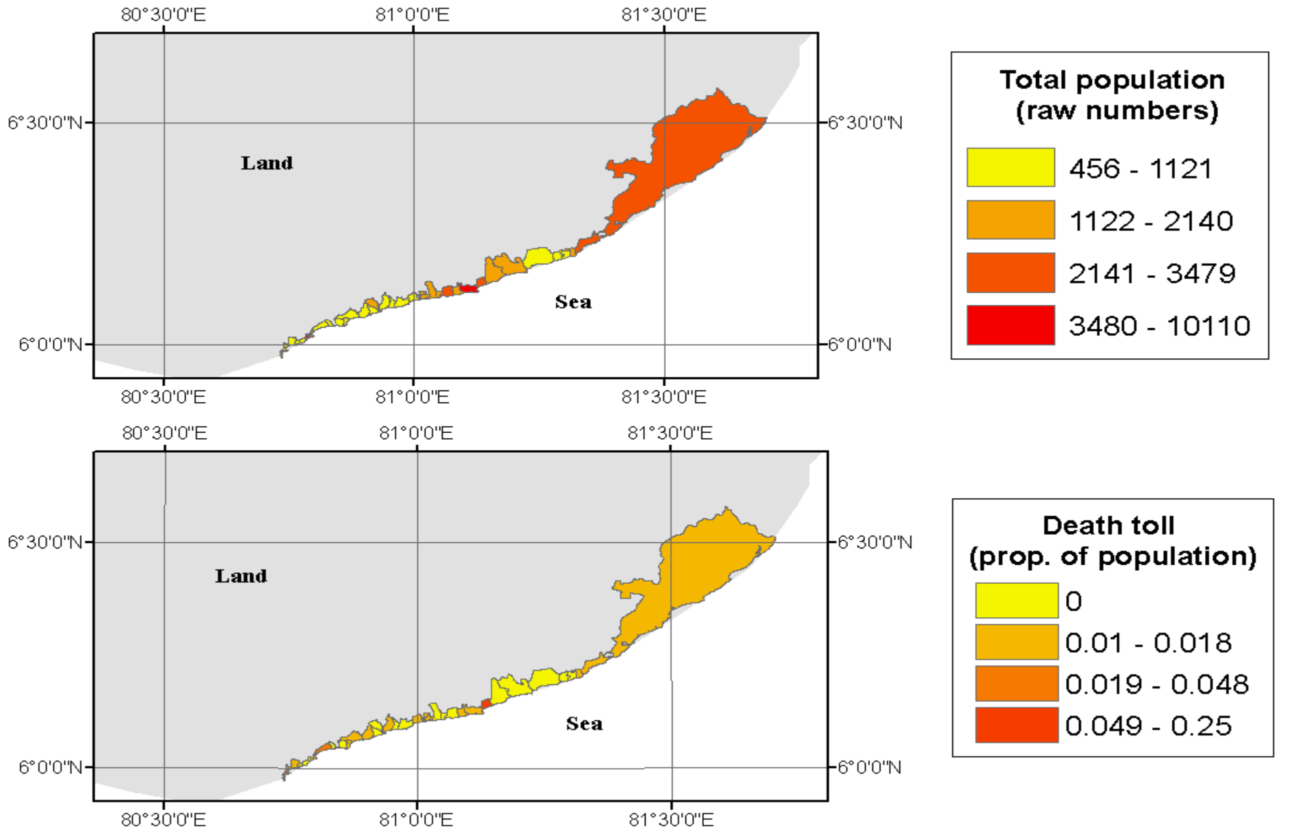

Figure 5.2 Map showing the total population and tsunami related death toll as proportion of the population for GN divisions in Hambantota, Sri Lanka.

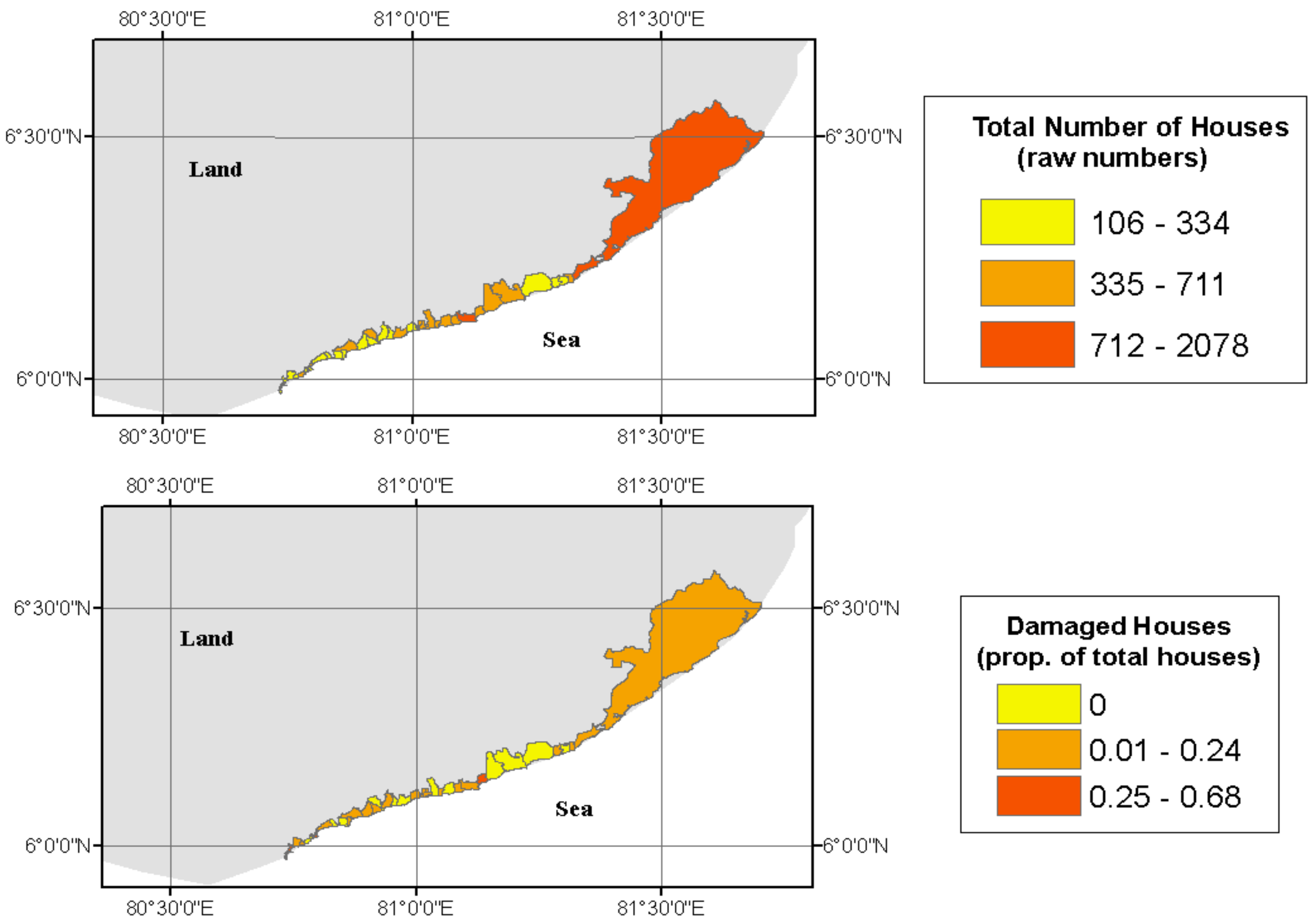

Figure 5.3 Map showing the total number of houses and the proportion of houses damaged as a result of the 2004 tsunami in Hambantota, Sri Lanka.

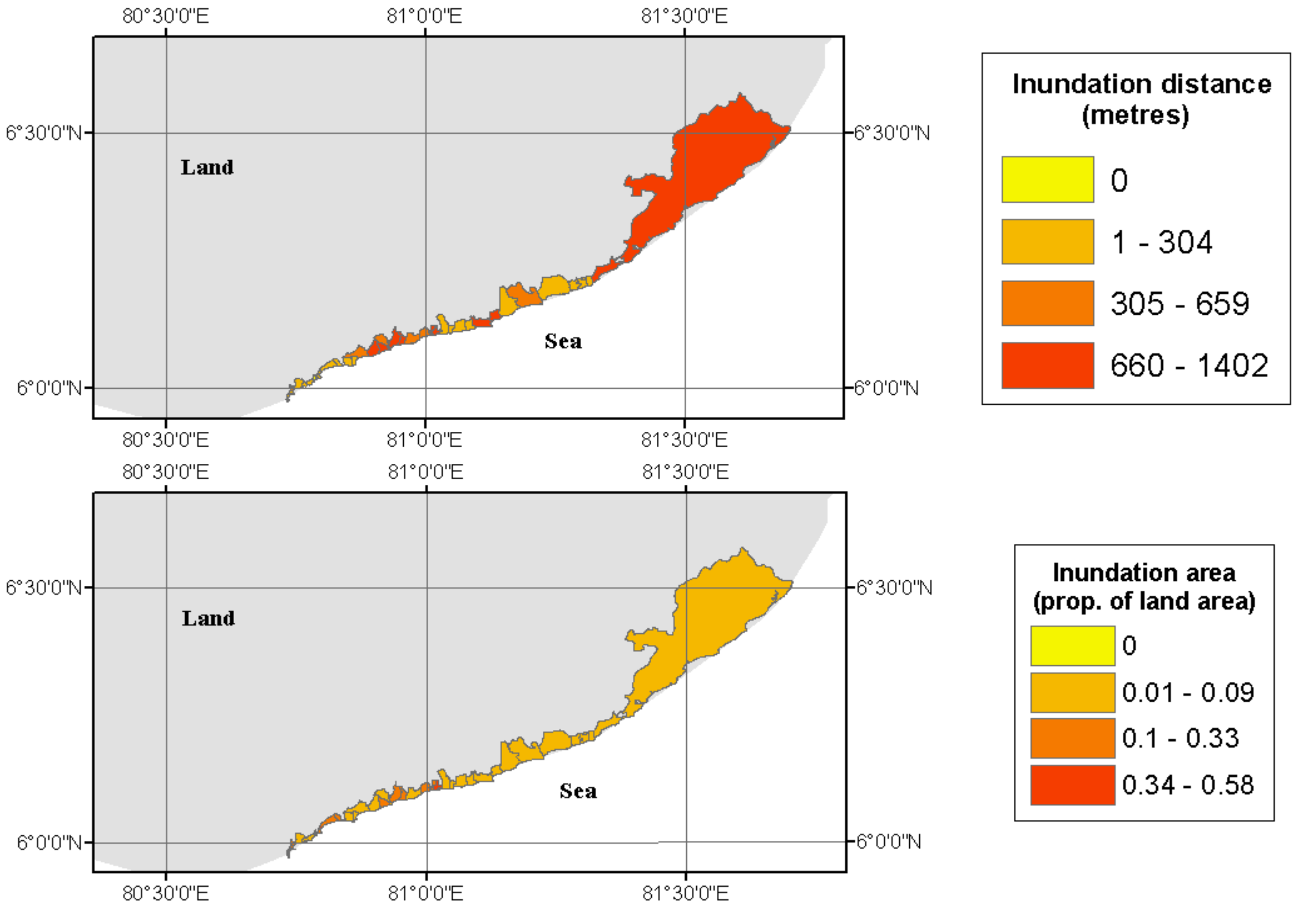

Figure 5.4 Map showing the degree of inundation experienced by each GN division in terms of both distance inundated and proportion of land inundated in Hambantota, Sri Lanka.

Subunits

A total of 335 subunits were constructed along the coast, giving a more in-depth data set with which to analyse inundation. Figure 5.5 shows inundation distance and inundation area for each of these subunits.

Figure 5.5 demonstrates the geographic difference between inundation distance and the proportion of area inundated as described for GN divisions. However, in this case both inundation distance and the proportion of area inundated are significantly positively correlated ($R_s = 0.79$, $p < 0.05$), despite differences in visual patterns. Variations within the boundaries of GN divisions are visible at this smaller spatial scale when compared to the patterns shown in Figure 5.4.

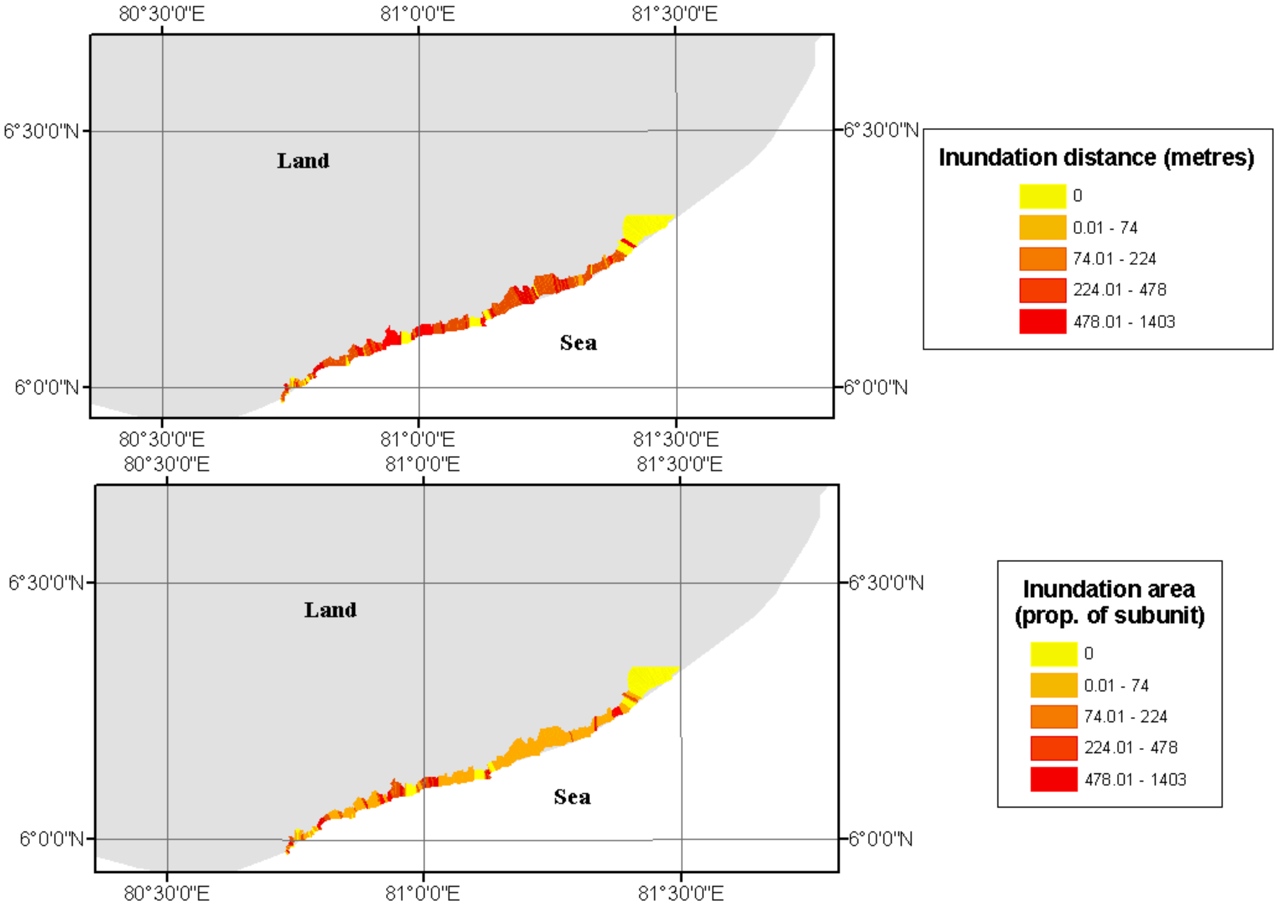

Figure 5.5 Map showing the degree of inundation experienced by each subunit in terms of both distance inundated and proportion of land inundated in Hambantota, Sri Lanka.

5.3.2. *Ecosystems and land uses in Hambantota*

The final GIS map for the coast of Hambantota is shown in Figure 5.6. The diversity and variability of land uses and ecosystems within this region is evident. South-eastern areas appear to be dominated by residential areas, whereas those further north and west appear to have a greater proportion of forest and coral reefs.

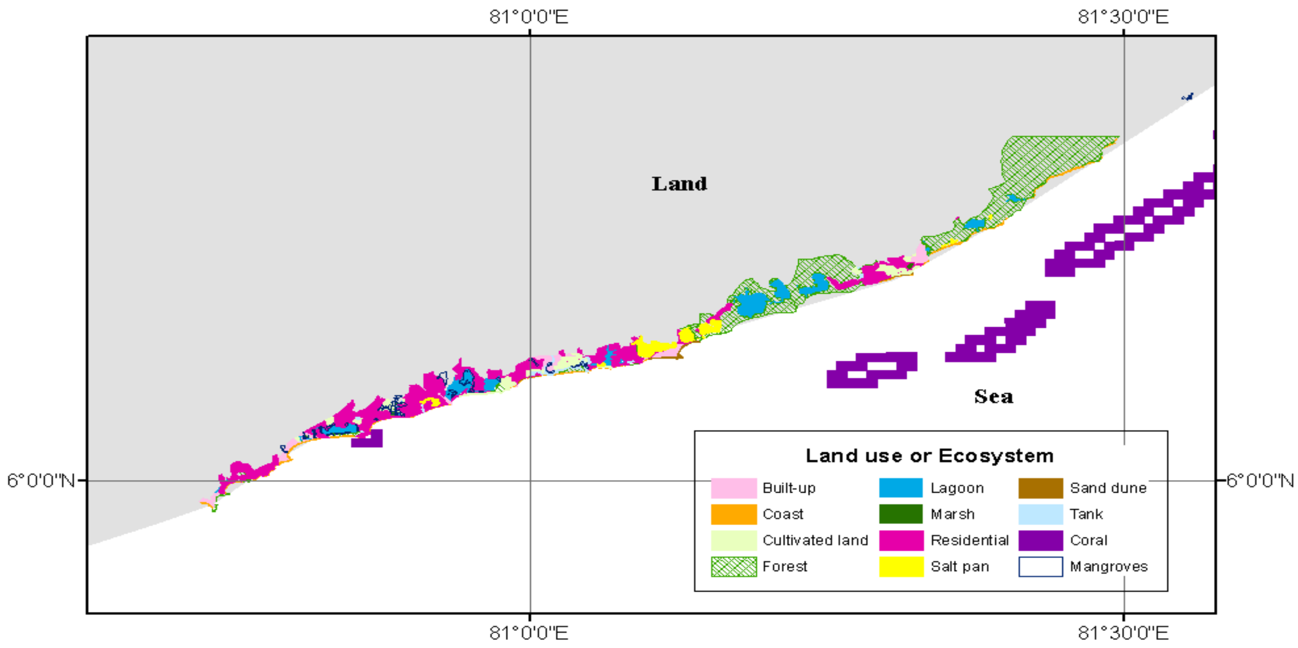

Figure 5.6 Map showing the land uses and ecosystems present within Hambantota, Sri Lanka. Mangroves are shown as unfilled polygons outlined in dark blue as a result of their overlap with areas of lagoon.

5.3.3. ***Physical attributes of Hambantota***

Bathymetry

A random sample of the total 335 transects is plotted in Figure 5.7. The coastline is represented by a blue line and three distinct points of inflection are marked with green lines. The three points of inflection were defined as the first occurrence of the ocean floor dropping below 100m, 500m and 4000m respectively.

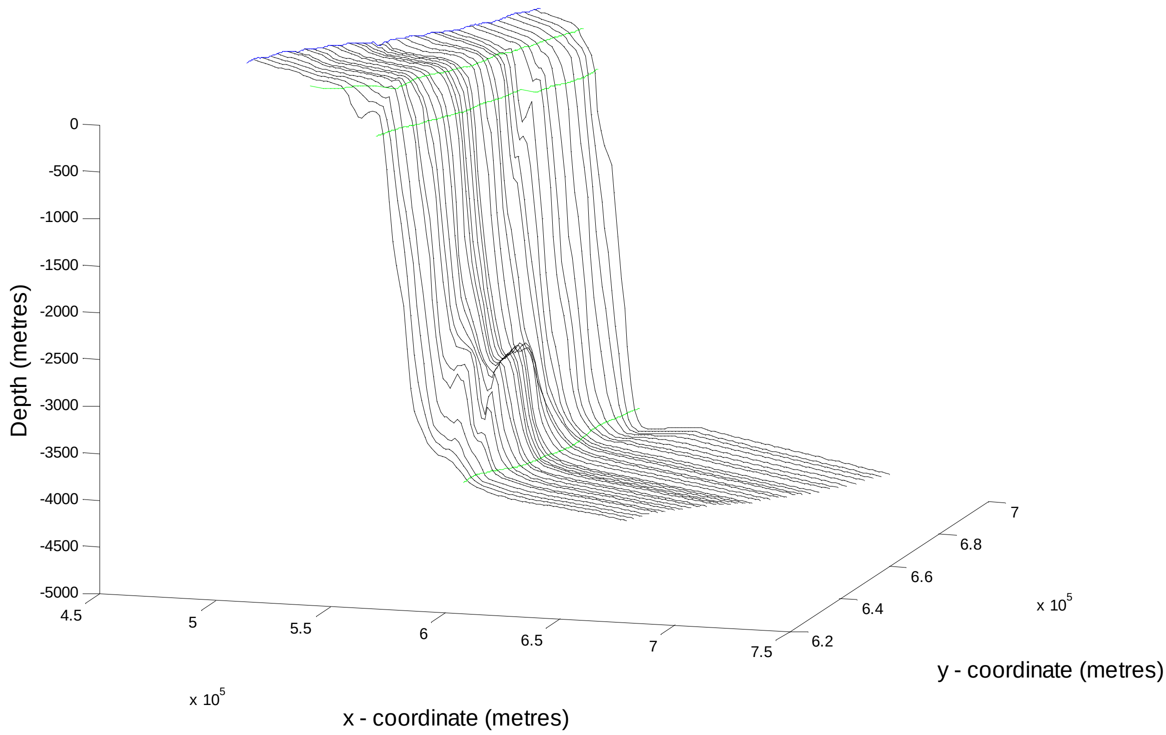

Figure 5.7 Three dimensional plot showing bathymetry transects along the Hambantota coast. For clarity, 1 in 10 transects is plotted rather than all 336. The blue line indicates the shoreline and green lines indicate the point of transition between the three distinct slopes.

The gradient and length of the ocean floor between the coast and the first point of inflection was calculated. Length and slope were also quantified between successive points of inflection. A total of 3 measurements for gradient and length were therefore taken characterising 3 slopes (slope A, slope B and slope C) for each subunit. The ranges of these values are shown in Table 5.3.

Table 5.3 The range of gradients and lengths for the three slopes measured.

Category	Minimum/maximum for slopes	Minimum/maximum for length (metres)
Slope A	-0.004/-0.001	24037/63920
Slope B	-0.137/-0.114	2941/35132
Slope C	-0.160/-0.075	22092/46792

To determine a value for each GN division, the mean average from all transects within the boundaries of a given GN division was utilised. This process was repeated for each of the three slopes.

Topography

The minimum, mean and maximum height above sea level was calculated within each GN division and within each subunit. Data for mean height above sea level for subunits are presented in Figure 5.8. The maps compiled show that the majority of subunits have a mean height above sea level in the lowest category of between 1.56 m and 7.02 m.

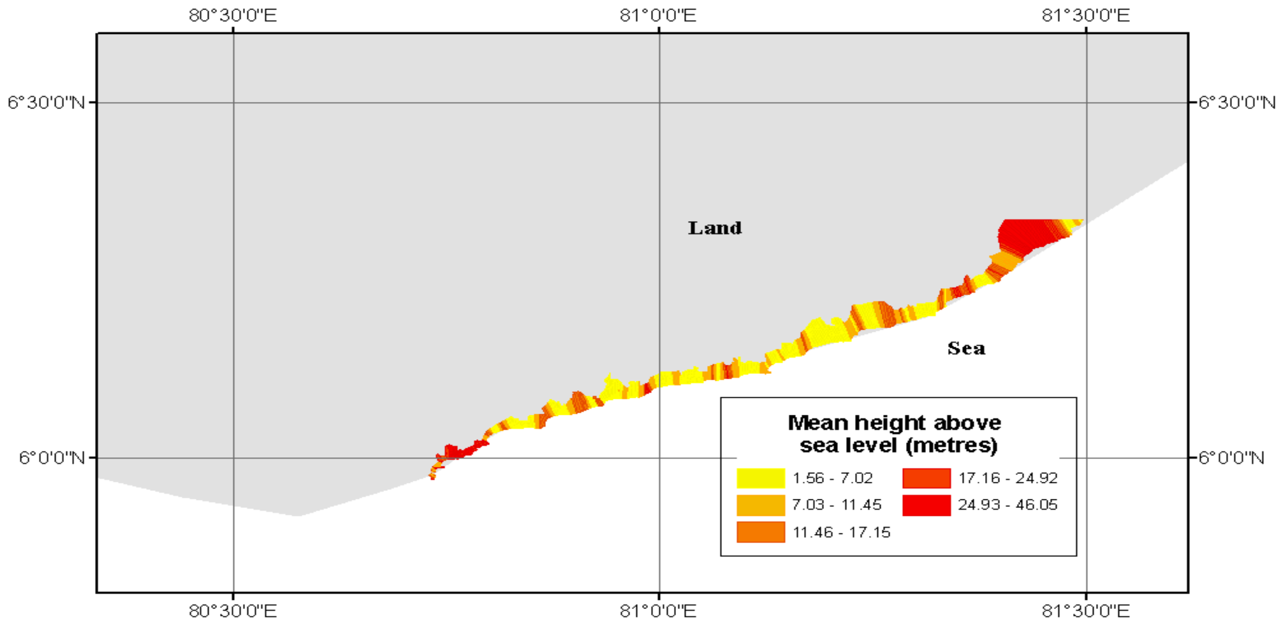

Figure 5.8 Map showing a graduated scale for the mean height above sea level within each subunit in Hambantota, Sri Lanka.

Coastal shape

Concavity measures for GN divisions and subunits are summarised in Table 4. The raw values were categorised to define each subunit/GN as having an approximately straight, convex or concave coastline. GN divisions and subunits were classified as straight if subtraction of angle 2 from angle 1 (Fig 5.1) was between -15° and 15°, convex if it was < -15° and concave if it was >15°.

Table 5.4 Minimum, maximum and interquartile range of values representing the degree of concavity of the coastline for GN divisions and subunits. The number of GN divisions or subunits consequently classified as approximately straight, convex and concave are shown.

Category	Minimum	Maximum	IQR	No. classified as approx. straight	No. classified as convex	No. classified as concave
GN division	-85.15	71.73	-18.96/16.47	19	10	10
Subunits (over 600m)	-178.34	174.91	-7.72/13.04	203	58	74
Subunits (over 6km)	-164.66	138.03	-13.88/13.77	178	80	77

Coast angle

Coast angles for GN divisions ranged between 15.09° and 84.95°, whereas at the finer resolution of subunits this range was extended to between -89.98 and 89.66. However in both cases the majority of angles were greater than 50°.

5.4. Discussion

5.4.1. ***Hambantota demographics***

Correlation results indicate that there is not always a quantifiable relationship between different measures of tsunami impact. Only two of the four measures extracted are correlated with one another (Table 5.2). This association was between death toll and damage to housing units. An association is likely to exist between these two variables, because death toll was measured by the Department of Census and Statistics, by recording the number of human fatalities within each damaged housing units.

The lack of association between all four indicators makes a strong case for the use of multiple indicators of impact when assessing which risk factors influenced tsunami impact. Existing multivariable models utilise only inundation distance (Chatenoux & Peduzzi 2005) as a proxy for tsunami impact. This may not adequately represent areas most severely impacted, in terms of death toll and housing damage. Areas shown in this chapter to have a large inundation distance can have a very small inundation area. Likewise, areas where inundation area is large may not be areas where the tsunami intruded a great distance.

All four measures described here will therefore be utilised in modelling which factors significantly influenced tsunami impact in Chapter 6.

Results indicate that inundation can be more accurately modelled using subunits rather than GN divisions, where detail on the extent of inundation is often masked by the large spatial scale. Housing damage and death toll must still be modelled using GN division data, as information on a finer spatial scale is not available.

5.4.2. ***Ecosystems and land uses in Hambantota***

A wide range of land uses and ecosystems are found in Hambantota. Areas primarily dominated by both natural ecosystems and development exist within the research area and further demonstrates the suitability of Hambantota for this research area. Heterogeneous sampling areas, in terms of the biophysical environmental and land-use, are more likely to identify potential risk factors, than more uniform sampling areas.

5.4.3. ***Physical attributes of Hambantota***

Bathymetry is a highly complex factor, which has very specific interactions with tsunami propagation and wave height (Duong *et al.* 2008). The measurements taken for this study probably give an over-simplified estimate of the ocean profile, but should be an adequate bathymetric characterisation for the purposes of the risk model.

Both subunits and GN divisions are dominated by approximately straight stretches of coastline. However, concavity of coast is shown to vary along the coast, particularly in the case of subunits. Similarly, topography also differs along the coast, despite the majority of subunits classified in the lowest height category.

Coast angle is indicative of the angle at which the tsunami struck. Although there is some variation depending on the abundance of projections and inlets along the coast, the majority of the Hambantota coast is orientated in a similar direction, and most angles were > 50 degrees.

5.4.4. ***Conclusions***

It is concluded that the Hambantota coastline is a suitable research area for modelling tsunami risk factors, with varied ecological, development and geomorphic characteristics. Models for inundation are likely to be more accurate using the finer spatial scale of subunits that incorporate more detail in explanatory (risk factors) and outcome variables (impact indicators). The absence of correlation between physical and socioeconomic indicators of tsunami damage highlights the importance of modelling the affect of risk factors on all measures of impact (e.g. inundation, death toll, housing damage). Housing damage and death toll statistics are available for each GN division and can therefore be modelled at this level.

6. Modelling ecological and other risk factors influencing the outcome of the 2004 tsunami in Sri Lanka

6.1. Introduction

According to eye-witness accounts and rapid assessment, natural systems, including mangroves, coral reefs and sand dunes, helped reduce damage through dissipation of wave energy, absorption of tsunami waters and by acting as physical barriers (Chapter 4; Atapattu 2005, Bambaradeniya et al. 2005, IUCN 2005, Kar and Kar 2005, Wabnitz et al. 2005; Venkatachalam et al. 2009). Post-tsunami field studies have supported these accounts, suggesting that villages behind coastal systems (i.e. mangroves, reefs and dunes) were better protected than those in more exposed locations (Danielsen et al. 2005, Kathiresan and Rajendran 2005, Chang et al. 2006, Ranasinghe and Kallesoe 2006) and that the aerial root system of mangroves increased drag force and trapped floating objects (Tanaka et al. 2007). Additionally, simulated experiments and some theoretical models have concluded a protective value for coastal forests (Harada et al. 2002, Irtem et al. 2009).

Other research, however, suggests that the protective role of natural systems has been overstated, attributing variation in tsunami impact to elevation, exposure and distance inland (Dahdouh-Guebas et al. 2006, Kerr et al. 2006, Kerr and Baird 2006, Kerr and Baird 2007, Baird and Kerr 2008, Feagin et al. 2010). Studies claiming the protective role of coral reefs (Fernando and McCulley 2005) and mangroves (Dahdouh-Guebas et al. 2005) have been criticised for not including these or other potential confounding factors (Baird et al. 2005, Baird 2006, Feagin et al. 2010). Initial statistical modelling considering the effects of various risk factors on tsunami inundation distance identified bathymetric features, elevation and seagrass as important determinants of protection (Chatenoux and Peduzzi 2005), whereas coral reefs were identified as exacerbating impact. Mangroves occurred only in sheltered bays and their protective role could not be easily determined.

Landscape analysis assessing the vulnerability of the Aceh coastline of Sumatra coastline provided further evidence for distance from the shore and elevation as important tsunami risk factors, but also identified vegetation type as an important factor. Developed areas sustained greater damage than forested zones (Iverson and Prasad 2007, 2008). Similarly, research between sites of comparable dimensions (considering bathymetry, coastline and exposure), but of differing vegetation, concluded villages behind mangroves were damaged less than more exposed locations (Chang et al. 2006).

Several post-tsunami research papers have therefore recommended the implementation of bioshields (Osti et al. 2009, Tanaka et al. 2009) and projects involving restoration and plantation of mangroves with the expectation of improved shoreline protection have been implemented (IUCN 2006b). Projects have been openly opposed by local fishing communities and researchers (Rodriguez et al. 2008) due to fears that other important natural systems such as sand dunes, which may have afforded physical protection against the tsunami wave, were being used as sites for revegetation (Bhalla 2007).

Policies in Sri Lanka implemented immediately after the 2004 tsunami also promoted relocation of communities on the coast inland, in favour of a setback zone, to help safeguard critical systems (CCD 2005, Wong 2009). Although later revoked, some communities had already been relocated with severe social and economic impact (Harris 2005, Leckie 2005, Rice 2005).

This chapter incorporates information from the previous chapter and uses statistical models as a basis for examining the credibility of questionnaire findings (Chapter 4 and Chapter 7). It has two main aims. First, to determine the degree to which potential risk factors, in terms natural systems and land use/development (e.g. built up town centres, residential housing, roads), influenced tsunami damage. This is based upon models using data on human deaths, housing damage, inundation distance and the proportion of land inundated as impact indicators. Second, to compare these findings with existing modelling studies, based solely upon inundation distance of the tsunami wave as the measure of impact (Adams et al. 2005, Chatenoux and Peduzzi 2005, Chang et al. 2006, Iverson and Prasad 2007). This chapter concludes by considering the relevance of tsunami related issues and wider environmental concerns to coastal policy setting in Sri Lanka.

6.2. Methods

6.2.1. ***The study area***

Coastal administrative district Hambantota (Fig 6.1) was selected for this research, for its unique attributes and suitability for examining tsunami risk factors, as described in Chapter 4, Section 4.2.1 and Chapter 5.

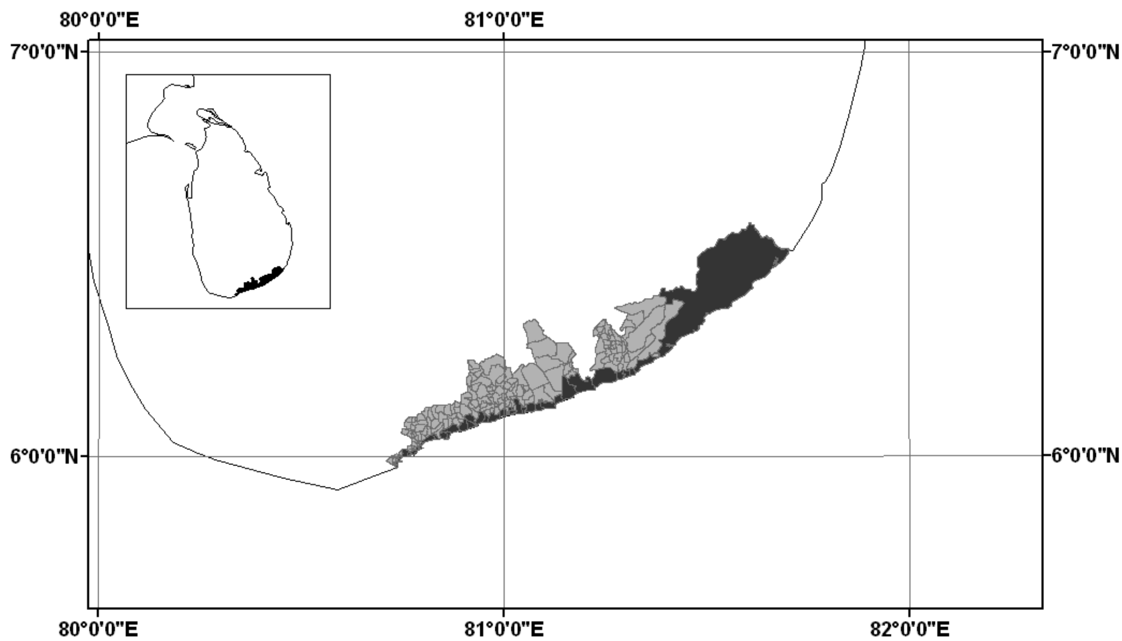

Figure 6.1 Map showing the location of Hambantota, the study area, on the southern coast of Sri Lanka. Coastal GN divisions are shaded in black.

The chapter focuses on the coastal GN divisions in Hambantota. This area encompasses 39 GN divisions in total within Tissamaharamaya, Hambantota, Ambalantota and Tangalle Divisional Secretariats.

6.2.2. ***Tsunami impacts/outcome variables***

Tsunami impact was quantified in terms of inundation, defined as the rising or flow of tsunami waters over land. Inundation was measured and modelled as (Model 1) a simple binary measure of whether the tsunami inundated/encroached onto land, (Model 2) the maximum distance travelled inland and (Model 3) the proportion of total land area covered by tsunami water. The Hambantota coastline was split, arbitrarily, into lengths of 300 m, allowing the creation of 335 units extending from the coastline to the inland boundary of each coastal GN division. All measures of inundation were extracted for the 335 units from maps provided by Sri Lanka's Coast Conservation Department (see Chapter 5; CCD 2008) and used to build separate models.

The number of damaged and destroyed housing units (Model 4), and the death count associated with each destroyed/damaged housing unit (Model 5), were determined for each GN division (n=39). These measures provided additional impact indicators. Both housing damage and death toll figures were obtained from the Department of Census and Statistics, Sri Lanka, a government department which collected data on 2004 tsunami damage and impact (see Chapter 5; DCS 2004, 2007). Models for housing damage and death toll were restricted to a smaller sample size of 39, representing the coastal GN divisions within Hambantota as data was not available at a finer resolution.

The degree of association between the four indicators of impact (maximum distance travelled inland, proportion of total land area covered by tsunami water, housing damage and death toll) were assessed in Chapter 5 (Table 5.2) to determine the effects of modelling tsunami impact by these different measures. Correlations between death toll and housing damage were carried out on raw count data rather than the binary variables utilised in Model 4 and 5.

6.2.3. ***Model 1: Tsunami inundation***

A logistic regression model with binary outcome was used to determine factors affecting whether the tsunami inundated or not. Explanatory variables for this model were quantified within a 15 m buffer zone from the coastline as follows:

$$\mathbf{\ln [p/(1-p)] = \beta_0 + \sum \beta_k X_k}$$

where ln [p/(1-p)] is the logit transform, β_0 is the intercept and X represents the series of predictor variables.

6.2.4. ***Model 2: Maximum inundation distance***

Of those subunits where inundation did occur, the inundation distance was modelled. Data were normalised by log transformation and a linear regression model was used to examine univariable and multivariable associations between inundation distance and potential explanatory variables with structure as follows:

$$\mathbf{y = \beta_{0i} + \beta_1 X_1 + \ldots + \beta_k X_k + \varepsilon}$$

Where β_0 is the intercept, X represents the series of predictor variables and ε is the error (Dohoo et al. 2009).

6.2.5. ***Model 3: Proportion of land inundated***

As inundation area represented, the proportion of each GN division inundated by the tsunami, a binomial family, logit link general linear model (Papke and Wooldridge 1996) was used, as shown below (Larget 2007):

$$\mathbf{E(y) = f^{-1} (\beta_{0i} + \beta_1 X_1 + \ldots + \beta_k X_{k})}$$

Where β_0 is the intercept, X represents the series of predictor variables and f represents the link function.

6.2.6. ***Models 4 and 5: Housing damage and death toll***

In order to more accurately model housing damage (Model 4) and death toll (Model 5), these count variables were later converted to binary variables, where 0 and 1 represented whether or not a GN division experienced housing damage or loss of human life. Data was modelled using a logistic regression model with structure as described for Model 1.

6.2.7. ***Model outputs***

In all five models predictor variables were first tested at the univariate level. Variables showing association with the outcome variable ($p \leq 0.05$) were tested in multivariable models and finalised using stepwise backward elimination. Coefficients for Model 2 were anti-logged to correct for the initial log transformation of data. In the case of odds ratios and coefficients, values >1 indicate an exacerbating effect of a factor on tsunami impact, while values < 1 signify a protective effective.

6.2.8. ***Predictor variables***

Predictor variables/potential tsunami risk factors were extracted from both published and unpublished sources (Table 6.1). Data were used to construct a GIS map in ArcView (ESRI Inc. 1999-2006), demarcating land uses, habitats, and tsunami inundation areas within each GN division (LUPPD 2007) and also within each of the 335 constructed subunits (see Chapter 5). Details describing the treatment, extent and sources of ecosystem/land uses and geomorphic variables are shown in Table 6.1 and 6.2 respectively. Predictor variables which did not show linearity with model outcomes were categorised. Land uses/ecosystems which were present only in a few sampling regions (GNs/subunits), such as mangroves, were entered into the model as a binary rather than quantitative inputs.

Table 6.1 Sources of information for ecosystems/land uses potentially influencing tsunami impacts in the Hambantota region of Sri Lanka. The table describes how the relevant data were extracted from each source. The range in numerical values entered into models is shown, indicating whether values were binary, categorical or continuous.

Predictor variable	Source of information	Extraction	Numerical values for model variables
Coral reef	Sheppard et al. (1996-1997), Spalding et al. (2001)	Presence or absence of coral reefs offshore from each GN division within direction of tsunami epicentre assessed visually and recorded as a binary (0,1) variable.	**Models 1-5:** (0,1)
Mangroves and marsh	Sheppard et al. (1996-1997), Spalding et al. (1997)	Mangrove and marsh presence absence within inundation area of each GN division or subunit assessed visually from two data sources and combined. Mangrove and marsh were first calculated separately and later combined to create a single binary (0,1) variable.	**Models 1-5:** (0,1)
Forest	Mapping carried out by CCD (LUPPD 2007,CCD 2008).	Areas (m^2) of each individual land use/ biological system within tsunami inundation area delineated and calculated using standard techniques in ArcView (ESRI Inc. 1999-2006). Areas were later converted to a proportion of the total inundation area and entered into models as categorical or binary (0,1) variables depending on their extent.	**Model 1: (0,1)** **Model 2&3:** 1 = 0-0.5 2 = >0.5-0.9 3 = > 0.9 **Model 4&5: (0,1)**
Sand dune			**Model 1:** (0,1) **Model 2:** (0,1) **Model 3:** 1 = 0-0.1 2 = >0.1-0.7 3 = > 0.7 **Model 4&5:** (0,1)
Salt Pan			**Models 1-5:** (0,1)
Bodies of water including lagoons, tanks and reservoirs.			**Model 1:** (0,1) **Model 2&3:** 1= 0-0.1 2 = >0.1-0.7 3 = >0.7 **Model4&5: (0,1)**
Cultivated			**Model 1:** (0,1) **Model 2:** (0,1) **Model 3:** (0,1) **Model 4&5: (0,1)**
Coast			**Model 1:** (0,1) **Model 2&3:** (0,1) **Model 4&5:** 1 = 0-0.1 **2 =** > 0.1-0.7 **3 =** > 0.7
Built-up			**Model 1:** (0,1) **Model 2&3:** 1 = 0- 0.1 **2** = > 0.1-0.9 **3** = > 0.9 **Model 4&5:** (0,1)
Residential			**Model 1:** (0,1) **Model 2:** 1 = 0-0.1 **2 =** >0.1-0.75 **3 =** > 0.75 **Model 3:** 1 = 0-0.1 **2 =** >0.1-0.75 **3 =** > 0.75 **Model 4 &5:** (0,1)
Proportion of natural systems to development	Satellite imagery and aerial photography (Sheppard et al. 1996-1997, LUPPD 2007, CCD 2008).	Land uses classified as natural or manmade. Total area for each summed and a ratio taken to indicate whether a GN division or subunit was predominately natural or developed.	**Model 2&3**: 0- 24355.66 **Model 4&5:** 0.001- 159000000
Minimum distance to residential and built up areas	Mapping carried out by the CCD (LUPPD 2007, CCD 2008).	Calculated only for death toll and housing damage models. Minimum distance to built-up or residential areas measured for each GN division.	**Models 1-3: N/A** **Model 4&5:** 0- 4236 metres

Table 6.2 Source of information for geomorphic features potentially influencing tsunami impacts in the Hambantota region of Sri Lanka. The table describes how the relevant data were extracted from each source. The range in numerical values entered into models are shown, indicating whether values were binary, categorical or continuous.

Predictor Variable	Source of information	Extraction	Extent
Bathymetry	GEBCO digital atlas (IOC et al. 2003)	200 m transects drawn for each subunit and converted to (x,y,z) coordinates. Coordinate values exported to Matlab and plotted. Three distinct slopes were identified for characterization: Slope A: between coastline and where profile first drops below 100m Slope B: between point where the profile first drops below 100m and where it first drops below 500m Slope C: between the point where the profile first drops below 500m and where it first drops below 4000m Lengths and gradients for each of these slopes were calculated, and values from subunits lying within GN division boundaries were averaged for Models 4 and 5. In the case of bathymetric slope gradients all three were treated as one variable representing the bathymetric profile of each GN/subunit. (See Chapter 5)	**Slope A gradient** **Models 1-3** 1= > -0.0023701 2= ≤ -0.0023701 **Models 4&5** 1= > -0.002 2= ≤ -0.002 **Slope A length (m)** **Models 1-3** 1=24000-32000 2=32001-48750 3=487501-63950 **Models 4&5** 1=26600-46200 2=46601-51000 3=51001-63500 **Slope B gradient** **Models1-3** 1= > -0.049 2= ≤ -0.049 **Models 4&5** 1= > -0.05 2= ≤ -0.05 **Slope B length (m)** **Models 1-3** 1=2900-6700 2=6701-9750 3=9751-35500 **Models 4&5** 1=3100-6850 2=6851-9800 3=9801-29250 **Slope C gradient** **Models1-3** 1= > -0.081314 2= ≤ -0.081314 **Models 4&5** 1= > -0.08 2= ≤ -0.08 **Slope C length (m)** **Models 1-3** 1=22000-40170 2=40171-43900 3=43901-46800 **Models 4&5** 1=24700-43560 2=43561-44640 3=44641-46610
Topography	SRTM (90m) Digital Elevation Model downloaded from the CGIAR Consortium for Spatial Information (Jarvis et al. 2008)	Minimum, mean and maximum height above sea level extracted for each subunit and GN division. All measures entered into models to ensure associations with topography were identified. (See Chapter 5)	**Minimum Ht above sea level** **Models 1-5** 1= ≤ 1 2= >1-4 3= >4 **Maximum Ht above sea level** **Models 1-5** 1= >9 - 20 2= >20- 26 3= >26 **Mean Ht above sea level** **Models 1-5** 1=>1-7.5 2= >7.5- 12 3= >12
Coastal Shape	Maps showing the Sri Lankan coastline (LUPPD,2007)	Coastal shape determined over a 600m and 6 km scale for subunits and on a scale dependent on GN division size for GN division (see Chapter5).	**Model 1-5:** 1= -15-15 (approx. straight) 2= < -15 (convex coastlines) 3= > 15 (concave coastlines)
Coastal Angle	Maps showing the Sri Lankan coastline (LUPPD,2007)	Coastal angle in relation to north for each subunit/GN calculated by constructing a line between the midpoints of adjacent subunits/GN divisions and calculating its angle using standard trigonometry techniques. (See Chapter 5)	**Model 1-3:** 1= <0 2= >0-22.5 3= >22.5-45 4= >45- 67.5 5= >67.5 **Model 4&5** 1= ≤ 50º 2 = > 50º

6.3. Results

6.3.1. *Outcome variable characterisation and inter-correlation*

Of the four measures of tsunami impact examined, only housing damage and death toll showed significant (positive) inter-correlation at the GN level (See Chapter 5; Table 5.2). Variable distributions for each of the five tsunami outcomes are shown as frequency data (Fig 6.2). Model results are described below for each model, at the univariate and multivariable level.

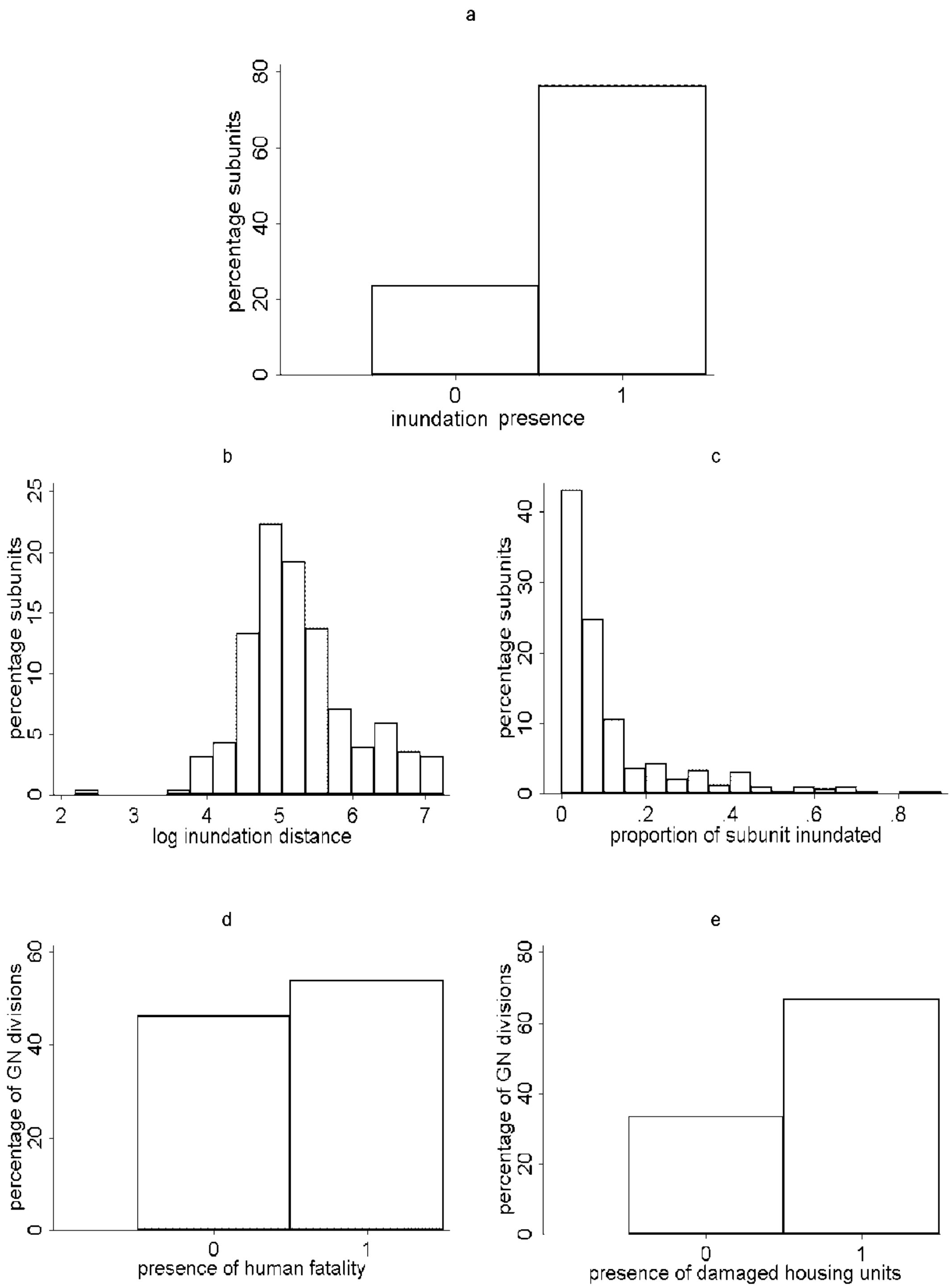

Figure 6.2 Plots showing distribution and range of the following model outcome variables: (a) Presence or absence of tsunami inundation (model 1), (b) Maximal inundation distance (logged) (model 2), (c) Proportion of area/land inundated (model 3), (d) Presence or absence of damaged housing units (model 4), (e) Presence or absence of human fatality (model 5).

6.3.2. ***Model 1: Factors influencing tsunami inundation***

Univariate logistic model results showing variables significantly influencing whether the tsunami inundated are shown in Table 6.3, and the final multivariable model is shown in Table 6.4. For the multivariable model, convex coastlines, minimum height above sea level and sand dune occurrence were protective factors, and bathymetry was also significant. Coastal areas with a steeper bathymetric gradient between 100-500 m depth (slope B) were more likely to inundate than shallower gradients. Additionally, coastal areas with a steeper gradient between 500- 4,000 m (slope C), were less likely to inundate.

Model fit was tested by the Hosmer-Lemeshow (H-L) statistic, and by calculating the area under the receiver operating characteristic (ROC) curve (Hardin and Hilbe 2007). The H-L χ^2 was 6.33 with $p>0.05$ and the ROC curve area was 0.86. These values suggest reasonable goodness of fit.

Table 6.3 Variables identified with univariate logistic regression models influencing whether or not the tsunami inundated Hambantota subunits.

Explanatory variable	Odds ratio	CI
Coast concavity (600 m) cat 1	baseline	-
Coast concavity (600 m) cat 2	0.49	0.26, 0.94
Coast concavity (600 m) cat 3	0.87	0.46, 1.66#
Coast concavity (6 km) cat 1 (straight coast)	baseline	-
Coast concavity (6 km) cat 2 (convex coast)	0.34	0.19, 0.61
Coast concavity (6 km) cat 3 (concave coast)	1.02	0.51, 2.05#
Coral absence	baseline	-
Coral presence	0.26	0.15, 0.47
Forest absence	baseline	-
Forest presence	0.57	0.34, 0.95
Maximum ht above sea level category 1	baseline	-
Maximum ht above sea level category 2	0.40	0.22, 0.73
Maximum ht above sea level category 3	0.15	0.07, 0.31
Mean ht above sea level category 1	baseline	-
Mean ht above sea level category 2	0.91	0.43, 1.93
Mean ht above sea level category 3	0.47	0.25, 0.88
Minimum ht above sea level category 1	baseline	-
Minimum ht above sea level category 2	0.29	0.16, 0.54
Minimum ht above sea level category 3	0.23	0.09, 0.57
Sand Dune absence	baseline	-
Sand Dune presence	0.25	0.10, 0.62
Bathymetry:		
Slope A gradient (> -0.002)	baseline	-
Slope A gradient steeper slopes (≤ -0.002)	0.45	0.27, 0.77
Slope B gradient (> -0.049)	baseline	-
Slope B gradient steeper slopes (≤ -0.049)	5.16	2.86, 9.32
Slope C gradient (> -0.081)	baseline	-
Slope C gradient steeper slopes (≤ -0.081)	0.34	0.20, 0.58
Slope A length category 1	baseline	-
Slope A length category 2	4.29	2.23, 8.24
Slope A length category 3	4.25	2.24, 8.06
Slope B length category 1	baseline	-
Slope B length category 2	0.13	0.05, 0.36
Slope B length category 3	0.08	0.03, 0.20
Slope C length category 1	baseline	-
Slope C length category 2	4.62	2.38, 8.98
Slope C length category 3	3.98	2.12, 7.47

within the confidence interval (CI) column indicates the variable category not significant (p>0.05).

Table 6.4 Model 1 showing factors significantly associated with whether the tsunami inundated Hambantota subunits at the multivariable level.

Explanatory Variable	Odds ratio	CI
Coast concavity (6 km) cat 1 (straight coast)	Baseline	-
Coast concavity (6 km) cat 2 (convex coast)	0.33	0.16, 0.68
Coast concavity (6 km) cat 3 (concave coast)	0.83	0.36, 1.95#
Minimum ht above sea level category 1	baseline	-
Minimum ht above sea level category 2	0.31	0.15, 0.65
Minimum ht above sea level category 3	0.18	0.06, 0.58
Sand dune absence	baseline	-
Sand dune presence	0.03	0.01, 0.11
Bathymetry:		
Slope A gradient (> -0.002)	baseline	-
Slope A gradient steeper slopes (≤ -0.002)	1.39	0.54, 3.58#
Slope B gradient (> -0.049)	baseline	-
Slope B gradient steeper slopes (≤ -0.049)	10.41	4.40, 24.63
Slope C gradient (> -0.081)	baseline	-
Slope C gradient steeper slopes (≤ -0.081)	0.12	0.04, 0.30

within the confidence interval (CI) column indicates the variable category not significant (p>0.05).

6.3.3. ***Model 2 and 3: Factors influencing maximum inundation distance and proportion of land inundated***

Significant univariate associations between explanatory variables and inundation measures are shown in Table 6.5. The final multivariable model for maximum inundation distance and proportion land inundated are shown in Table 6.6 and 6.7 respectively. For both multi-variable Models 2 and 3, water bodies and saltpans exacerbated damage (inundation distance and proportion of land inundated) while coasts, beaches and sand dunes were protective. Rock also increased the proportion of land inundated (Model 3).

Deviance residuals for Model 2 were shown to be approximately normal by examination of probability plots and through the Shapiro-Wilkinson test for normality (z=0.968, $p \geq 0.05$). Removal of outliers did not significantly change results (6 outliers removed in total). The link specification test and the Ramsey regression specification error test both had p values ≥0.05, indicating correct model specification.

Table 6.5 Odds ratios/coefficients and confidence intervals for tsunami impact model based on explanatory variables associated with the two inundation outcomes (p≤0.05) at the univariate level.

Explanatory Variable	Model 2 inundation distance		Model 3 inundation area	
	Coefficient	CI	Odds ratio	CI
Body of water category 1	baseline	-	baseline	-
Body of water category 2	1.99	1.49, 2.72	5.26	3.68, 7.53
Body of water category 3	3.32	2.23, 4.90	5.08	2.42, 10.66
Built-up category 1	baseline	-	baseline	-
Built-up category 2	1.70	1.27, 2.25	3.30	2.15, 5.07
Built-up category 3	1.20	0.83, 1.73#	4.93	3.01, 8.08
Coast absence	baseline	-	baseline	-
Coast presence	0.56	0.44, 0.72	0.20	0.13, 0.29
Coast concavity (6km) cat 1 (straight coast)	baseline	-	baseline	-
Coast concavity (6km) cat 2 (convex coast)	0.70	0.56, 0.89	0.43	0.29, 0.65
Coast concavity (6km) cat 3 (concave coast)	1.11	0.90, 1.36#	1.02	0.72, 1.47#
Coral presence	0.66	0.57, 0.79	0.49	0.35, 0.68
Cultivated land absence	baseline	-	-	-
Cultivated land presence	1.72	1.26, 2.36	-	-
Forest category 1	baseline	-	baseline	-
Forest category 2	0.57	0.42, 0.79	1.16	0.67, 2.03#
Forest category 3	0.70	0.58, 0.84	0.37	0.28, 0.49
Marsh and mangrove absence	baseline	-	baseline	-
Marsh and mangroves presence	1.80	1.38, 2.36	2.83	1.81, 4.42
Maximum ht above sea level category 1	baseline	-	baseline	-
Maximum ht above sea level category 2	0.90	0.71, 1.16#	0.48	0.34, 0.68
Maximum ht above sea level category 3	0.38	0.25, 0.57	0.22	0.13, 0.40
Mean ht above sea level category 1	baseline	-	baseline	-
Mean ht above sea level category 2	1.08	0.87, 1.35#	1.06	0.71, 1.59
Mean ht above sea level category 3	0.74	0.61, 0.90	0.60	0.40, 0.90
Minimum ht above sea level category 1	baseline	-	-	-
Minimum ht above sea level category 2	0.90	0.71, 1.16#	-	-
Minimum ht above sea level category 3	0.38	0.25, 0.57	-	-
Residential category 1	baseline	-	-	-
Residential category 2	1.55	1.09, 2.20	-	-
Residential category 3	1.05	0.85, 1.28#	-	-
Rock absence	-	-	baseline	-
Rock presence	-	-	4.84	1.96, 11.93
Salt pan absence	baseline	-	baseline	-
Salt pan presence	2.80	1.60, 4.90	3.51	1.95, 6.33
Sand dune category 1	baseline	-	baseline	-
Sand dune category 2	0.59	0.42, 0.85	0.77	-
Sand dune category 3	-	-	0.20	0.06, 0.62
Bathymetry:				
Slope A gradient (> -0.002)	baseline	-	baseline	-
Slope A gradient steeper slopes (≤ -0.002)	0.70	0.59, 0.83	0.52	0.37, 0.73
Slope B gradient (> -0.049)	baseline	-	baseline	-
Slope B gradient steeper slopes (≤ -0.049)	0.88	0.74, 1.05#	0.82	0.60, 1.13#
Slope C gradient (> -0.081)	baseline	-	baseline	-
Slope C gradient steeper slopes (≤ -0.081)	0.71	0.60, 0.84	0.43	0.30, 0.61
Slope A length category 1	baseline	-	baseline	-
Slope A length category 2	1.25	1.001, 1.53	1.01	0.64, 1.59#
Slope A length category 3	1.73	1.39, 2.13	2.12	1.36, 3.31
Slope B length category 1	baseline	-	-	-
Slope B length category 2	1.62	1.34, 1.95	-	-
Slope B length category 3	0.81	0.66, 0.99	-	-
Slope C length category 1	baseline	-	baseline	-
Slope C length category 2	1.27	1.02, 1.58	1.03	0.67, 1.61#
Slope C length category 3	1.69	1.36, 2.12	2.09	1.34, 3.28

#within the confidence interval (CI) column indicates the variable category not significant (p>0.05).

Table 6.6 Model 2 showing factors associated with the maximum tsunami inundation distance within subunits at the multivariable level.

Explanatory variable	Coefficient	CI
Body of water category 1	baseline	-
Body of water category 2	1.05	0.84, 1.32#
Body of water category 3	1.88	1.40, 2.48
Built-up category 1	baseline	-
Built-up category 2	2.14	1.72, 2.66
Built-up category 3	1.51	1.15, 1.95
Coast absence	baseline	-
Coast presence	0.82	0.68, 0.99
Cultivated land absence	baseline	-
Cultivated land presence	1.43	1.15, 1.79
Minimum ht above sea level category 1	baseline	-
Minimum ht above sea level category 2	0.91	0.76, 1.09#
Minimum ht above sea level category 3	0.51	0.38, 0.70
Salt pan absence	baseline	-
Salt pan presence	2.46	1.70, 3.56
Sand dune absence	baseline	-
Sand dune presence	0.60	0.45, 0.78
Slope B length category 1	baseline	-
Slope B length category 2	0.96	0.79, 1.17#
Slope B length category 3	0.34	0.26, 0.45
Bathymetry:		
Slope A gradient (> -0.002)	baseline	-
Slope A gradient steeper slopes (≤ -0.002)	0.99	0.81, 1.21#
Slope B gradient (> -0.049)	baseline	-
Slope B gradient steeper slopes (≤ -0.049)	0.45	0.36, 0.57
Slope C gradient (> -0.081)	baseline	-
Slope C gradient steeper slopes (≤ -0.081)	1.05	0.88, 1.25#

within the confidence interval (CI) column indicates the variable category not significant (p>0.05).

Table 6.7 Model 3 showing factors associated with proportion of subunit land inundated by tsunami waters at the multivariable level.

Explanatory variable	Odds Ratio	CI
Body of water category 1	baseline	-
Body of water category 2	2.45	1.57, 3.82
Body of water category 3	2.94	1.46, 5.92
Built-up category 1	baseline	-
Built-up category 2	2.14	1.40, 3.29
Built-up category 3	4.97	2.88, 8.59
Coast concavity (6km) cat 1 (straight coast)	baseline	-
Coast concavity (6km) cat 2 (convex coast)	0.55	0.39, 0.78
Coast concavity (6km) cat 3 (concave coast)	0.76	0.56, 1.03#
Coast absence	baseline	-
Coast presence	0.28	0.19, 0.43
Forest category 1	baseline	-
Forest category 2	1.54	0.90, 2.63#
Forest category 3	0.52	0.35, 0.78
Mean ht above sea level category 1	baseline	-
Mean ht above sea level category 2	0.82	0.57, 1.17#
Mean ht above sea level category 3	0.63	0.44, 0.90
Rock absence	baseline	-
Rock presence	2.62	1.59, 4.34
Salt pan absence	baseline	-
Salt pan presence	3.02	1.78, 5.12
Sand dune category 1	baseline	-
Sand dune category 2	0.92	0.45, 1.91#
Sand dune category 3	0.25	0.07, 0.87
Bathymetry:		
Slope A gradient (> -0.002)	baseline	-
Slope A gradient steeper slopes (≤ -0.002)	1.16	0.79, 1.69#
Slope B gradient (> -0.049)	baseline	-
Slope B gradient steeper slopes (≤ -0.049)	0.82	0.62, 1.11#
Slope C gradient (> -0.081)	baseline	-
Slope C gradient steeper slopes (≤ -0.081)	0.70	0.49, 0.99

within the confidence interval (CI) column indicates the variable category not significant (p>0.05).

6.3.4. *Model 4 and 5: factors influencing housing damage and death toll*

Bathymetry, in terms of the gradient of slope C, was the only variable shown to be associated with housing damage at both the univariate level and the multivariable level (PRR=0.10, CI=0.02, 0.65) when combined with slope A gradient (PRR=1.56, CI= 0.34, 7.29) and slope B gradient (PRR=1.57, CI= 0.25, 9.77). The H-L χ^2 value was 2.21 with p values $\geq$ 0.05 and the ROC curve area was 0.77, suggesting a reasonable fit.

Univariate associations with explanatory variables and death toll per damaged housing unit are shown in Table 6.8 and multivariable associations are shown in Table 6.9. Built up areas was a risk factor exacerbating death toll. For the multivariable model the H-L χ^2 value was 4.90 with p value $\geq$ 0.05 and the ROC curve area was 0.88, suggesting a reasonable fit.

Predictor variables/risk factors measuring the same or similar parameters (for example bathymetric slopes with bathymetric lengths and minimum, mean and maximum heights above sea level) showed significant positive correlation with one another.

Table 6.8 Model 4. Odds ratios for explanatory variables associated with the presence or absence of human fatalities in Hambantota GN divisions (p≤0.05); CI confidence interval.

Explanatory variable	Odds ratio	CI
Bathymetry:		
Slope A gradient (> -0.002)	baseline	-
Slope A gradient steeper slopes (≤ -0.002)	1.3	0.36, 4. 68#
Slope B gradient (> -0.049)	baseline	-
Slope B gradient steeper slopes (≤ -0.049)	0.73	0.21, 2.57#
Slope C gradient (> -0.081)	baseline	-
Slope C gradient steeper slopes (≤ -0.081)	0.12	0.23, 0.51
Built-up areas absence	baseline	-
Built-up areas presence	6.67	1.47, 30.21
Coast concavity cat 1 (straight coast)	baseline	-
Coast concavity cat 2 (convex coast)	3.25	0.66, 15.98
Coast concavity cat 3 (concave coast)	19.5	1.99, 190.88

within the confidence interval (CI) column indicates the variable category not significant (p>0.05).

Table 6.9 Model 4. Multivariable model showing odds ratios for explanatory variables associated with the presence or absence of human fatalities in Hambantota GN divisions (p≤ 0.05)); CI confidence interval.

Explanatory variable	Odds ratio	CI
Bathymetry:		
Slope A gradient (> -0.002)	baseline	-
Slope A gradient steeper slopes (≤ -0.002)	2.00	0.36, 11.22#
Slope B gradient (> -0.049)	baseline	-
Slope B gradient steeper slopes (≤ -0.049)	6.00	0.50, 72.36#
Slope C gradient (> -0.081)	baseline	-
Slope C gradient steeper slopes (≤ -0.081)	0.03	0.002, 0.45
Built-up areas absence	absence	-
Built-up areas presence	9.48	1.26, 71.24

within the confidence interval (CI) column indicates the variable category not significant (p>0.05).

6.4. Discussion

Analysis of different indicators of tsunami impact showed significant correlation only between housing damage and death toll. Neither inundation distance, a measure of tsunami damage impact used in earlier models (Chatenoux and Peduzzi 2005), or inundation area, showed significant auto-correlation or correlation with housing damage or death toll (See Chapter 5; Table 5.2). This highlights the importance of utilising multiple indicators of impact in assessments of risk factors which influenced the outcome of the 2004 tsunami.

Whether or not the tsunami wave inundated (Model 1) is shown to be influenced by bathymetric slope, coast concavity and height above sea level in terms of geomorphic features. Gradients for bathymetric slopes B and C (the two most seaward slopes) remained significant in the multivariable model. A steeper gradient for slope C appears to have been protective against tsunami inundation. This supports earlier studies stating that shallow slopes exacerbated impact (Chatenoux and Peduzzi 2005). However, in the case of slope B the opposite effect was observed, where areas with a steeper gradient in this region were more likely to be inundated. Convex coastlines at the 3 km scale were shown to be protective compared to a straight coastline, perhaps by deflecting tsunami waters to adjacent areas. The greater the minimum height above sea level for a given subunit of the Hambantota coast the more likely it was to be protected from tsunami intrusion. This finding agrees with previous reports and studies (Chatenoux and Peduzzi 2005, Kathiresan and Rajendran 2005, Kerr et al. 2006), demonstrating that elevation was a key factor which helped to reduce tsunami impact. Additionally, sand dunes within the first 15 m of the coastline were shown to be protective against intrusion of tsunami waters. They likely acted as a physical barrier by effectively increasing the height above sea level of the coastline. Sand dunes have been suggested as important in recent reports, where authors fear their importance for coastal defence has been overlooked in favour of bioshields (Bhalla 2007).

The degree of tsunami inundation (Models 2 & 3) is shown to be associated with a number of factors. Systems/land uses which acted as risk factors, by increasing inundation distance and inundation area, were bodies of water including tanks, reservoirs and lagoons, the presence of salt pans and built up areas. Bodies of water were significantly associated with increased inundation distance when their area exceeded 70% of the sample area. Inundation area was also associated with bodies of water when they covered 70% of the subunit area and also when they covered 10%-70% of the subunit area when compared to the baseline, comprising subunits where < 10% was occupied by water. Areas of water most likely provided an easier path for tsunami intrusion inland particularly when they were open to the coast. This is congruent with previous research which identifies bodies of water such as rivers as exacerbating tsunami impacts (Yasuda et al. 2006). However, examination of maps indicates that the area covered in these instances predominantly constitutes the body of water itself. Therefore despite a larger inundation area, this may not equate to greater damage to infrastructure. Salt pans are low lying surfaces which are likely to provide little frictional resistance to tsunami waters which may explain why they are a significant factor in increasing inundation. Similarly, built-up areas where there is likely to be a high percentage of paved areas and areas cleared from vegetation would provide a reduced frictional force and absorption capacity.

Cultivated land exacerbated inundation distance and the presence of rock exacerbated inundation area. Cultivated land, similarly to salt pan, is often low lying flat expanses of land, perhaps facilitating the path for tsunami intrusion and thus increasing the distance that water travelled. There is qualitative evidence for this association given that many farmers relying on cultivated land suffered as a result of salt intrusion caused by the tsunami waters travelling over their crops (Kielen 2005, Chandrasekharan et al. 2008). Areas of rock are often located along the coastal edge and were therefore the first land use/ecosystem the tsunami encountered. These areas are likely to provide very little friction force and in some subunits encompassed a large lateral area along the coast perhaps facilitating intrusion on a large scale.

Land uses/ ecosystems shown to be protective in terms of both inundation distance and inundation area were the presence of a coast/beach area and sand dunes. The presence of an intact beach may have offered some frictional resistance to the tsunami wave, while sand dune probably afforded protection through their height and 3-dimensional structure.

Protective geomorphic variables associated with a reduced inundation distance and inundation area include both topographical and bathymetric features. Inundation distance was negatively associated with areas where the minimum height above sea level exceeded 4 m. Similarly, inundation area was reduced in areas where the mean height above sea level was > 12 m. This might be expected given findings of previous research as discussed under the results for Model 1, where existing research suggests that tsunami waters inundated up to the point at which height above sea level exceeded wave height. Model 3, representing inundation area, also agrees with Model 1 in identifying subunits where slope C (gradient between where the ocean floor drops between 500 m and 4000 m below sea level) was steeper (gradient ≤ -0.081) as having reduced tsunami impact. Although Model 2 does not identify this characteristic in slope C as being significant, it does identify slope B as being more protective when it was steeper (gradient ≤ -0.049). This differs from the result of Model 1, where steeper gradients of slope B were more likely to lead to tsunami inundation. Additionally, inundation distance models also identified the length of slope B as an important factor where slopes longer than 9,751 m experienced reduced inundation. This result was unexpected, given previous findings stating longer shallow slopes exacerbated impacts.

The inundation area model (Model 3) also identified forest as a protective feature, although only when it exceeded a large proportion (>90%) of the subunit area. Hence, despite forests' apparent protective influence, artificial creation of bioshields through revegetation may prove to be impractical, as they would need to cover over 90% of the land area. It is also noted that the 'forest' category does not include mangroves, an ecosystem that has been the subject of much debate in terms of their capacity to provide tsunami protection. At the univariate level, mangroves and marsh land (data undifferentiated) are actually associated with increased area of inundation. It may be because mangroves and marshes are often located in estuaries, lagoons and inlets (Hogarth 1999, Kathiresan and Qasim 2005) and bodies of water were shown to exacerbate damage in this study. Further, inundation measures were not correlated with death toll and housing damage. Hence, factors shown to influence inundation may not necessarily influence human fatality and infrastructure damage. However, this does not undermine the many other beneficial ecosystem services provided by coastal ecosystems such as mangroves.

Additionally, Model 3 showed agreement with Model 1 in that inundation area was negatively associated with convex coastlines. As discussed in the results of Model 1, convex coastlines on the 3 km scale are likely to have deflected tsunami waters to neighbouring areas, thus providing some 'local' protection.

Although wave height was originally a risk factor intended for inclusion in the model, a comprehensive dataset encompassing values for each GN division for southern Sri Lanka was not available. Tidal gauges are infrequent and post-tsunami survey teams did not systematically visit each coastal GN division in Hambantota. Therefore there was not enough information on the variability of wave heights along the coast to model their effect on impact. Seagrass was initially considered as a potential risk factor due to its significance in reducing tsunami inundation distance as identified in previous research (Chatenoux and Peduzzi 2005). However, there is no significant seagrass coverage within the research area (Green and Short 2007).

Few predictor variables showed associations with both housing damage and death toll. These results likely reflect low power due to a small sample size. In order to improve models, it would be beneficial to obtain death toll and housing damage data at the village level, allowing for smaller sampling areas and therefore a larger sample size. However, at the time of this study this data was not available. It is also noted that death toll used in these models is per damaged and destroyed housing unit. These values may not represent the absolute death toll for each GN division (i.e. some people may have died from non-damaged houses), although the two measures are likely to be associated.

In terms of housing damage and death toll, bathymetry is shown to be an important risk factor. GN divisions with a steeper slope C experienced a reduction in both number of deaths and number of damaged housing units. Further, bathymetric slope was the only explanatory variable shown to be associated with damaged housing units. This finding is in agreement with inundation models (Models 1-3) where bathymetry is also identified as an important indicator of impact. Death toll, however, was also shown to be associated with built-up areas. This was an unsurprising result given that these areas are likely to have a higher population. However, in addition to having a higher population, built-up regions were shown in models 2 and 3 to be positively associated with increased tsunami inundation.

In previous models, distance to villages has been shown to be a significant factor in terms of housing damage and property loss (Kathiresan and Rajendran 2005) h. Although not significant here, this may be due to built-up and residential areas as classified by the Coast Conservation Department giving an incomplete picture of the location of human populations. Site visits along the coast of Sri Lanka for questionnaire surveys revealed that a number of houses are not in areas classified as residential or built up. These houses are also likely to be closer to the coast and may therefore have experienced a greater proportion of damage or mortality.

Modelling tsunami impacts is highly complex and, as this chapter reveals, different indicators of impact can influence which variables appear important in influencing tsunami damage. This chapter shows that a number of factors significantly affected tsunami impacts. However, only bathymetry, a major determinant of tsunami wave height and force, was significant in all 5 models. Bathymetry is clearly not a factor that can be modified by human intervention to help provide protection. Tsunamis are rare, episodic events and the role of protective factors (e.g. dense forest, sand dunes) and factors associated with increased impact (e.g. built-up areas, water bodies) should also be examined in relation to more frequent events, such as monsoon and storm damage. Additionally, the wider role of different coastal systems and land uses, irrespective of any association with tsunami outcome, should be considered prior to future development activities involving coastal modification. Post-tsunami planning has not always encompassed all these factors. For example, local communities felt unsettled and in some cases without a viable livelihood when displaced inland, from the coastal setback zone (Harris 2005, Leckie 2005, Rice 2005, Rodriguez et al. 2008, Feagin et al. 2010). While future coastal policy setting in Sri Lanka should focus on prevailing environmental concerns, issues relating to episodic rare events such as tsunamis should not be overlooked.

7. General Discussion and Conclusions

7.1. Interpretation of results

7.1.1. *Human pressures and the status of Sri Lanka's coastal zone*

The ecosystems of Sri Lanka have been heavily degraded by both natural and anthropogenic pressures (Lowry 1994; Rajasuriya *et al.* 1995; Brown 1997; Wickremeratne & Samarakone 1997, Chapters 2 & 3). The research in this thesis assessed change, and the drivers of change, observed by fishers within fisheries Fisheries are an extremely important resource in Sri Lanka, where over half a million people are engaged in marine resource dependent livelihoods (MFAR & FAO 2006).

Fisheries were assessed in Chapter 3 through examination of catch statistics and questionnaire data on frigate tuna (A*uxis thazard*), a species commonly caught by artisanal fishers in Sri Lanka. No decadal patterns are evident from catch statistics between the years 1994 and 2004 for frigate tuna and bullet tuna combined, and there is no real evidence of fisheries decline (Venkatachalam *et al.* 2010). However, analysis of fisher opinions gave different results. *Questionnaire 2* asked three generations of fishers about the size of their best days catch, the largest fish they have ever caught and the distance offshore of these catches, in order to identify any changes in fishers 'baselines' depending on their age. The phenomenon of shifting baselines across fishers of different age groups has been observed in other fisheries worldwide (Pauly 1995; Baum & Myers 2004; Saenz-Arroyo *et al.* 2005a; Saenz-Arroyo *et al.* 2005b; Lozano-Montes *et al.* 2008). However, these studies have mainly observed change in larger pelagic species. In Sri Lanka, a declining trend was observed amongst frigate tuna (Chapter 3, section 3.3.2 & 3.3.3), despite their reported abundance worldwide (Uchida 1981) and the absence of evidence for decline from IOTC catch statistics. Younger fishers reported smaller catches and fish sizes and an increase in the distance offshore they landed these catches. Additionally, when data was analysed by the year that fishers caught their largest catch, rather than by age, a decline was also observed. This showed evidence of a marked decline in the fishery since 1951. The number of sites reported as having declined by fishers also increased as fishers age increased. These results give further evidence for over-harvesting of coastal fisheries in Sri Lanka and contradicts studies published in 1993 suggesting that frigate tuna stocks could be further exploited (with a 40% increase) to maximise yields (Dayaratne 1993).

The 2004 tsunami exerted further pressure on Sri Lanka's marine resources, albeit indirectly. Tsunami aid money was often targeted at fishing communities and spent on providing new equipment and boats to coastal communities (FAO 2005d). However, in many cases there was an over-provision to communities, with the number of glass-fibre boats granted by aid agencies exceeding the number of boats lost to the 2004 tsunami (in some cases doubling the size of pre-existing fishing fleets) (FAO 2005d; De Silva & Yamao 2007; MFAR 2007). Analysis of questionnaires administered to fishers in Hambantota provides further evidence of this phenomenon, with the median number of large and small boats reported by fishers significantly increasing in each of the communities interviewed (Chapter 3, section 3.3.4). However, very few fishers thought that fisheries decline was the result of this increase in equipment or a result of 2004 tsunami damage and mainly attributed declines to a larger new generation of fishers. The full effect of over-provision of boats remains to be seen in future research and catch statistics.

7.1.2. ***Coastal and socio-economic interactions with the 2004 tsunami: a synthesis***

The 2004 tsunami caused devastation within Sri Lanka and throughout the wider Indian Ocean. My research identifies factors which exacerbated and alleviated tsunami impact within Hambantota, Sri Lanka.

Studies published immediately after the 2004 tsunami to identify factors which provided protection mainly rely on eye witness accounts that have often been reported as quotations and comments (Bambaradeniya *et al.* 2005a; Brosnan 2005; Wabnitz *et al.* 2005; WI 2005). More in depth studies involved the identification of univariate correlations between damage and single ecosystems (Dahdouh-Guebas *et al.* 2005a; Danielsen *et al.* 2005; Kathiresan & Rajendran 2005). There are very few multivariate studies published since the 2004 tsunami. Studies which have been published are either large scale treating each country as a sampling site (Chatenoux & Peduzzi 2005) or have chosen sites with assumed similar characteristics for comparison (Adams *et al.* 2005; Chang *et al.* 2006) and do not necessarily quantify all land uses. Additionally, most studies to date use inundation distance alone as a proxy for tsunami damage.

My research firstly quantified the opinions of 500 fishers in Hambantota on factors they felt provided protection or exacerbated damage (Chapter 4). Findings were useful not only for developing preliminary conclusions about positive and negative risk factors and could also be used to inform policy makers and to develop hypothesis for further research. The landscape of Hambantota including ecosystems, land uses, topography and bathymetry were then quantified (Chapter 5) and entered into statistical models to determine which factors were associated with tsunami impact (Chapter 6).

The models presented in my thesis are believed to be the most in-depth studies to date. All land uses and resources were included in each model to identify potential associations with tsunami impacts, and four indicators of tsunami impact were modelled, defined as housing damage, death toll, proportion of area inundated and maximal inundation distance. This proved particularly important for Hambantota, where measures of inundation were shown not to be correlated with the anthropogenic measures of impact (Chapter 6).

The fishers in Hambantota believed that coral reefs, mangroves and sand dunes were the primary factors in providing protection against human fatality and housing damage, and that rivers/estuaries, concave coast lines, hotels and high beach slopes exacerbated these impacts. Through modelling of death toll and housing damage bathymetric features were the only factor found to be associated with both these measures of impact where steeper slopes provided protection. Additionally, increased human fatality and built up areas were also associated and shown to exacerbate damage which may reflect fisher opinions on hotels.

However, modelling of inundation did identify some of the same factors fishers felt were associated with human fatality and housing damage. Firstly, sand dunes were shown to be positively associated with reduced inundation distance and inundation area. This finding is particularly important as sand dunes have been mentioned in previous research as an ecosystem often over-looked when considering tsunami protection and in some countries are being cleared to make room for bioshields (Bhalla 2007). Concave coastlines, which were identified as protective by fishers were not associated with greater inundation, however, convex coastlines were protective, thus reducing inundation area. Bodies of water were also shown to exacerbate damage in agreement with fisher opinions on rivers and estuaries.

Regression models for inundation, housing damage and death toll revealed that mangroves were not associated with reduced impact as suggested by previous research (Dahdouh-Guebas *et al.* 2005a; Danielsen *et al.* 2005; Kathiresan & Rajendran 2005; Ranasinghe & Kallesoe 2006) and fishers (Venkatachalam *et al.* 2009, Chapter 4). Forests did have an association with reduced inundation area, but only when they occupied over 90% of the land area. This finding is extremely important in light of post-tsunami projects initiated in many Indian Ocean countries which have promoted bioshields (Bhalla 2007; Tanaka *et al.* 2009; Feagin *et al.* 2010) and mangrove replanting (IUCN 2006a) in hope of improved protection against future disasters. Many of the factors identified as providing tsunami protection cannot be easily changed or manipulated by human intervention to prevent impact from future disasters. For example, the only factor shown to be significant in affecting all indicators of impact was bathymetry, a factor suggested by some post-tsunami reports as being the primary determinant of impact (Chatenoux & Peduzzi 2005). Similarly, topography another factor identified as potentially important (Baird 2006), was shown to be significant, as greater heights above sea level reduced both the possibility of inundation and severity of inundation. All of the statistical models did provide a different set of explanatory variables highlighting the complexity of tsunami impact.

7.2. Critique of methodologies

Questionnaires are a useful method of gathering information and tapping into traditional ecological knowledge (Johannes 1998; Johannes *et al.* 2000). However, their utility can be greatly improved when combined with scientific surveys, experiments and statistics. Catch data was available on frigate tuna for comparison with fisher responses in Hambantota (Appendix 3, *Questionnaire 2*; Chapter 3).

However, catch statistics were combined with data for bullet tuna and missing data was a clear problem within the dataset (Venkatachalam *et al.* 2010). The study on frigate tuna would therefore have benefited from better comparative statistical and historical data, to determine if changes evident from fisher observations can also be traced within fishery records. In the absence of historical data, future monitoring programmes should endeavour to collect data at the individual species level.

Risk factor questionnaires (Appendix 4, *Questionnaire 3*; Chapter 4) gave a useful basis upon which to develop risk factor models. The value of tapping into indigenous and traditional ecological knowledge to improve information, resource management and to develop research hypotheses in both a fisheries and natural disasters context has already been noted. In the case of many of the risk factors identified by fishers, the pilot study and group discussions revealed reasons why fishers believed these factors affected tsunami impact. However, had more time been available, a more extensive questionnaire requiring fishers to explain why they believed each of these factors exacerbated or provided protection against tsunami impact would be useful. Additionally, some factors included in final regression models were not included in the risk factor questionnaires (e.g. topography, bathymetry). Information on the community's opinion on how it believed these factors might have influenced impact is therefore not available. However, factors such as bathymetry are not visible to the human eye and it is therefore unlikely fishers would have insight into how they influenced tsunami impact.

To my knowledge, the models presented in this thesis contain more detail than previously published research on tsunami risk factors. However, these models could still be improved to include greater detail. Factors such as bathymetry are highly complex. Although a rudimentary measure of this factor was included in all models, it could be improved using data at greater resolution. Using maps and sources of existing information was practical and saved time, however, more detailed information for some categories would have been helpful. Built up areas could be more clearly defined into towns, cities or into areas defined by their predominant building materials.

Models for human death toll and housing damage could also be vastly improved by the availability and incorporation of finer resolution data. These models were limited by census statistics, which were only available at the GN division level. Furthermore, the death toll statistics represented the number of people deceased in damaged housing units, and not the absolute total number of deaths within each GN division. Despite the lack of data available for some factors, these multivariable models including all possible land uses provide useful insight into factors which may have influenced socioeconomic tsunami impacts in addition to more physical signs of impact. In contrast, most existing studies have looked at inundation distance alone as an indicator of impact. In the absence of greater resolution data within the study area of Hambantota, future models could be extended to include all of Sri Lanka giving a greater sample size. Further research should also be carried out to determine the extent to which risk factors identified in Sri Lanka may also govern outcomes in other Indian Ocean countries, or if my results are specific to Sri Lanka.

7.3. Recommendations for policy makers

Effective and appropriate management of Sri Lanka's fisheries is extremely important. Given the post-tsunami increase in boats and fishing equipment (Chapter 3), it is likely to become an even more critical issue in years to come. Government bodies should therefore exercise care when licensing many of these newly donated boats, and also monitor their effect on catch per effort closely. Additionally, in order to improve current policies, a more effective monitoring system should be developed. Currently, fishery species are often grouped together for ease of data collection, particularly in the case of species considered of low or modest commercial importance. Future monitoring programmes should therefore record data at the individual species level. My research, using questionnaire data, has demonstrated that frigate tuna (*Auxis thazard)*, a species of local importance, is showing signs of depletion, despite reports (based on catch statistics) suggesting that it is abundant. Greater attention should therefore be given to protecting species important to artisanal fishers, and not just to those of current commercial value. In order to address these issues, the integration of fisher knowledge into monitoring programmes, as well as coastal and fishery policies, is seen as an important first step. This approach would not only give a more comprehensive assessment of stock abundance, but also reflect the concerns and interests of local coastal communities.

Protecting the coast of Sri Lanka from future episodic events, such as tsunamis, is highly complex. My research suggests that many of the factors showing the greatest effect on degree of tsunami impact are geographical features, such as topography and bathymetry, which are not easily altered by human intervention. However, some factors, such as sand dunes, could make a difference if they were protected. Although forests were identified as important in one of the models, they were only effective when they occupied over 90% of the research area. Additionally, mangroves were not a significant factor in any of the models, despite their perceived importance by fishers in southern Sri Lanka. This suggests that current bioshield plans may not suffice in providing protection against future tsunamis. Nevertheless, conservation and restoration of mangroves and forests remain important. However, this should be carried out for the purpose of preserving ecosystem functions unrelated to issues surrounding the 2004 tsunami, and not solely for the purpose of coastal protection against future tsunamis. Policy makers should be mindful that tsunamis are rare episodic events. Many of the factors reported here should be examined to determine their relationship with more frequent events, such as monsoon and storm damage. As in the case of fisheries, inclusion of indigenous peoples' opinions into policy development could help identify new factors and ensure better harmonisation of coastal communities' opinions with government policies and regulations.

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Appendices

Appendix 1. Questionnaire 1- Diver Questionnaire: Coral Reefs Evaluation in Southern Sri Lanka (2008)

Summary

A questionnaire was developed, requesting information from divers on changes in primary indicators of reef health along the southern and western coast of Sri Lanka. If a change was detected, respondents were then asked to what degree they felt that a predefined list of potential pressures had influenced the change. Questionnaires were administered to all dive centres and dive clubs (thirteen in total) along the southern and western coast (DiveSriLanka; Plunkett & Ellemor 2003; Solf 2008). Questionnaires were sent between May and September 2008 in both Sinhala and English via email and then followed up with a phone call. Descriptive statistics were produced to summarize the results.

Questionnaire

1a. Name of diving site/reef which you are referring to: 1b. GPS position if known:

2. Name of diver (or leave blank if you prefer)

3. Number of years diving experience on diving site?

4. Date when this form is completed

5. Change in **overall reef condition** since first visit to island (tick or * one category below):

large decrease	small decrease	no change	small increase	large increase

6. If you report a decrease, to what extent do you think the following factors have contributed to this change? 0=factor unimportant, 3=factor very important

Fishing pressures (including dynamite)	0	1	2	3
Aquarium trade	0	1	2	3
Removal of coral (mining, ornaments)	0	1	2	3
Recreation diving	0	1	2	3
Coastal development (including sedimentation)	0	1	2	3
Sewage/industrial discharges	0	1	2	3
Oil/pollution	0	1	2	3
Bleaching/ El Nino / high temperatures	0	1	2	3
Crown of thorns starfish/sea urchins	0	1	2	3
2004 *tsunami*	0	1	2	3
Other please specify	0	1	2	3

……………………………….

7. Change in **live coral cover** on reefs since first visit to island (tick or * one category below):

large decrease	small decrease	no change	small increase	large increase

8. If you report a decrease, to what extent do you think the following factors have contributed to this change? 0=factor unimportant, 3=factor very important

Fishing pressures (including dynamite)	0	1	2	3
Aquarium trade	0	1	2	3
Removal of coral (mining, ornaments)	0	1	2	3
Recreation diving	0	1	2	3
Coastal development (including sedimentation)	0	1	2	3
Sewage/industrial discharges	0	1	2	3
Oil/pollution	0	1	2	3
Bleaching/ El Nino / high temperatures	0	1	2	3
Crown of thorns starfish/sea urchins	0	1	2	3
2004 *tsunami*	0	1	2	3
Other please specify	0	1	2	3

……………………………….

9. Change in **coral varieties** on reefs since first visit to island (tick or * one category below):

large decrease	small decrease	no change	small increase	large increase

10. If you report a decrease, to what extent do you think the following factors have contributed to this change? 0=factor unimportant, 3=factor very important

Fishing pressures (including dynamite)	0	1	2	3
Aquarium trade	0	1	2	3
Removal of coral (mining, ornaments)	0	1	2	3
Recreation diving	0	1	2	3
Coastal development (including sedimentation)	0	1	2	3
Sewage/industrial discharges	0	1	2	3
Oil/pollution	0	1	2	3
Bleaching/ El Nino / high temperatures	0	1	2	3
Crown of thorns starfish/sea urchins	0	1	2	3
2004 *tsunami*	0	1	2	3
Other please specify	0	1	2	3

……………………………….

11. Change in **algal growth** on reefs since first visit to island (tick or * one category below):

large decrease	small decrease	no change	small increase	large increase

12. If you report an increase, to what extent do you think the following factors have contributed to this change? 0=factor unimportant, 3=factor very important

Fishing pressures (including dynamite)	0	1	2	3
Aquarium trade	0	1	2	3
Removal of coral (mining, ornaments)	0	1	2	3
Recreation diving	0	1	2	3
Coastal development (including sedimentation)	0	1	2	3
Sewage/industrial discharges	0	1	2	3
Oil/pollution	0	1	2	3
Bleaching/ El Nino / high temperatures	0	1	2	3
Crown of thorns starfish/sea urchins	0	1	2	3
2004 *tsunami*	0	1	2	3
Other please specify	0	1	2	3

……………………………….

13. Change in **reef fish abundance** since first visit to island (tick or * one category below):

large decrease	small decrease	no change	small increase	large increase

14. If you report a decrease, to what extent do you think the following factors have contributed to this change? 0=factor unimportant, 3=factor very important

Fishing pressures (including dynamite)	0	1	2	3
Aquarium trade	0	1	2	3
Removal of coral (mining, ornaments)	0	1	2	3
Recreation diving	0	1	2	3
Coastal development (including sedimentation)	0	1	2	3
Sewage/industrial discharges	0	1	2	3
Oil/pollution	0	1	2	3
Bleaching/ El Nino / high temperatures	0	1	2	3
Crown of thorns starfish/sea urchins	0	1	2	3
2004 *tsunami*	0	1	2	3
Other please specify	0	1	2	3

……………………………….

15. Change in **reef fish varieties** since first visit to island (tick or * one category below):

large decrease	small decrease	no change	small increase	large increase

16. If you report a decrease, to what extent do you think the following factors have contributed to this change? 0=factor unimportant, 3=factor very important

Fishing pressures (including dynamite)	0	1	2	3
Aquarium trade	0	1	2	3
Removal of coral (mining, ornaments)	0	1	2	3
Recreation diving	0	1	2	3
Coastal development (including sedimentation)	0	1	2	3
Sewage/industrial discharges	0	1	2	3
Oil/pollution	0	1	2	3
Bleaching/ El Nino / high temperatures	0	1	2	3
Crown of thorns starfish/sea urchins	0	1	2	3
2004 *tsunami*	0	1	2	3
Other please specify	0	1	2	3

……………………………….

17. Change in **pelagic/open water fish abundance** since first visit to island (tick or * one category):

large decrease	small decrease	no change	small increase	large increase

18. If you report a decrease, to what extent do you think the following factors have contributed to this change? 0=factor unimportant, 3=factor very important

Fishing pressures (including dynamite)	0	1	2	3
Aquarium trade	0	1	2	3
Removal of coral (mining, ornaments)	0	1	2	3
Recreation diving	0	1	2	3
Coastal development (including sedimentation)	0	1	2	3
Sewage/industrial discharges	0	1	2	3
Oil/pollution	0	1	2	3
Bleaching/ El Nino / high temperatures	0	1	2	3
Crown of thorns starfish/sea urchins	0	1	2	3
2004 *tsunami*	0	1	2	3
Other please specify	0	1	2	3

……………………………….

19. Incidence of coral bleaching (whitening from loss of associated zooxanthellae/algae): indicate years of occurrence:

20. Any additional notes:

Results : Reef condition determined from questionnaire survey of dive centres on the SW coast

Four of the thirteen dive centres/clubs approached were able to respond while four were thought to be closed down and the remaining five did not respond. Despite the response rate equating to 44% of the number of valid dive centres, this is not a sufficiently large sample size for statistical analysis. Factors unanimously considered to be important or unimportant are reported below.

Reefs named by respondents in the questionnaire were primarily located on the western and southern coast of Sri Lanka. Divers experience ranged from 6 to 16 years, therefore spanning the period from 1992 to 2008.

- Change in primary indicators of coral reef health during respondents time as a dive master

Patterns show that most of the primary indicators are reported by respondents as having changed (Fig A1.1). No change is reported fairly infrequently, reported twice by respondents with 6 years diving experience, once by a respondent with 10 years diving experience and not mentioned at all by the diver with 16 years experience. The drivers of changes in these primary indicators are examined, semi-quantitatively, in the following sections.

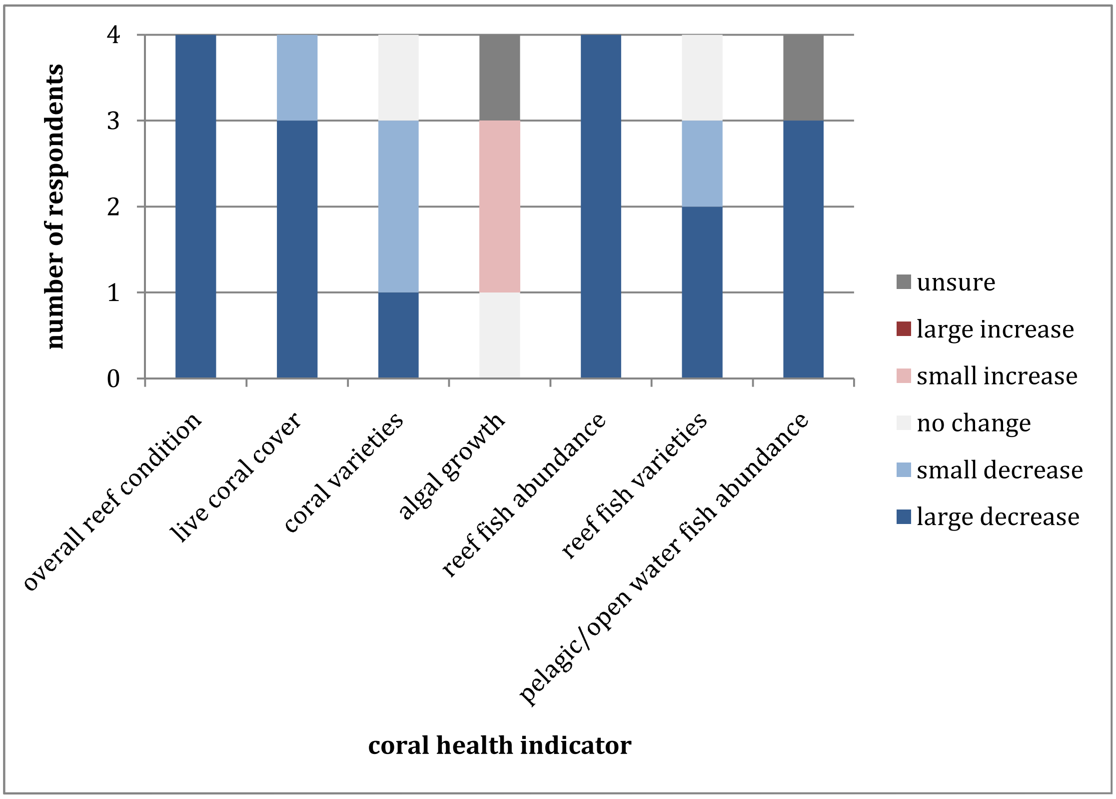


Figure A1.1 Perceived changes in indicators of coral reef health during the period of time each respondent has been diving.

- Overall reef condition

  All four respondents believed that there has been a large decrease in reef condition during the period of time they have been diving and that fishing pressures were very important in contributing to this (Fig A1.2). Additionally, bleaching was considered very important by three quarters of respondents and slightly important by 1 respondent in contributing to the decline. Three of the four respondents felt that the 2004 tsunami was at least slightly important and one respondent reporting on the changes in coral reef condition for Bar Reef felt that it was unimportant.

  Diving and the crown of thorns starfish were reported by all as being only slightly important or unimportant in influencing the reef condition decline.

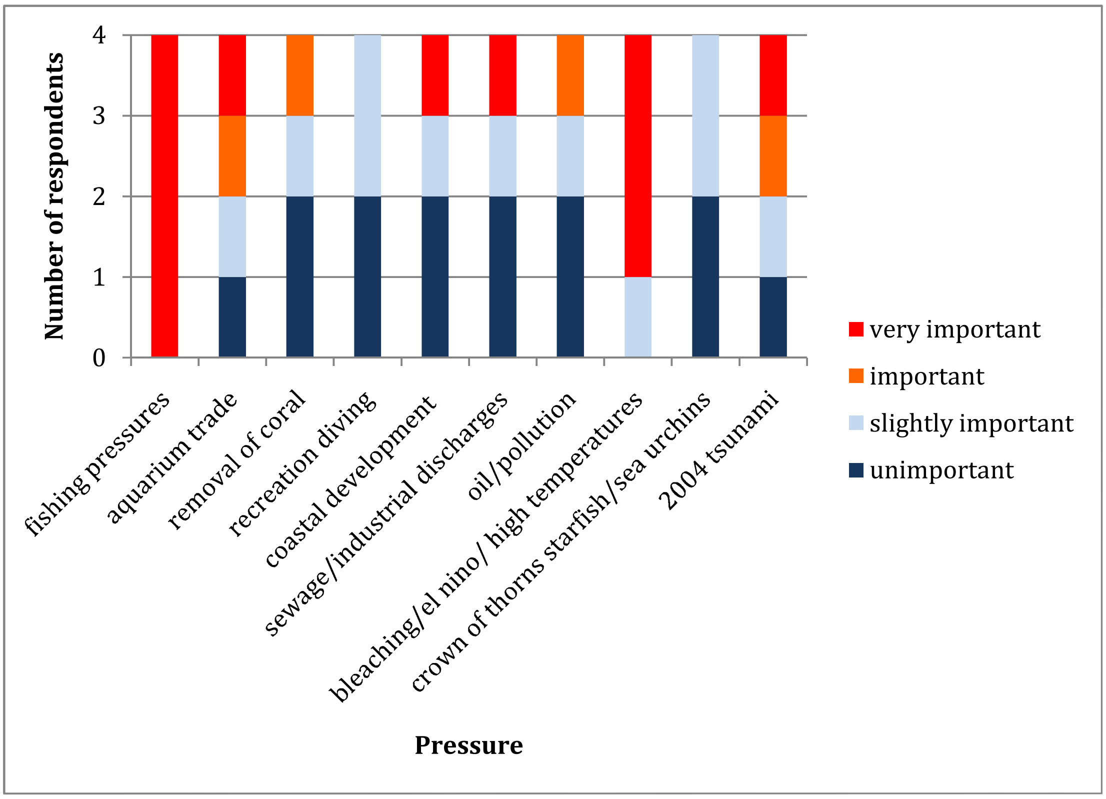


Figure A1.2 Perceived degree to which different pressures on coral reefs influenced changes in overall reef condition.

- Coral cover

  Three of the four respondents felt that coral cover had shown a large decrease within the years they had been diving which ranged from 6 to 16 years. One respondent felt that there had been a small decrease, within the 6 years they had been diving. Respondents unanimously identified fishing pressures as being at least slightly important in the decrease observed (Fig A1.3). Half the respondents felt that the aquarium trade was responsible for this decrease and 3/4 identified bleaching/El Niño events as influential. Two respondents whose answers related to Unawatuna and Hikkaduwa felt the 2004 tsunami was an important factor in decreasing coral cover.

  Three out of four respondents reported that effects from development, diving, sewage/industrial discharges and oil/pollution were not important in influencing coral cover change.

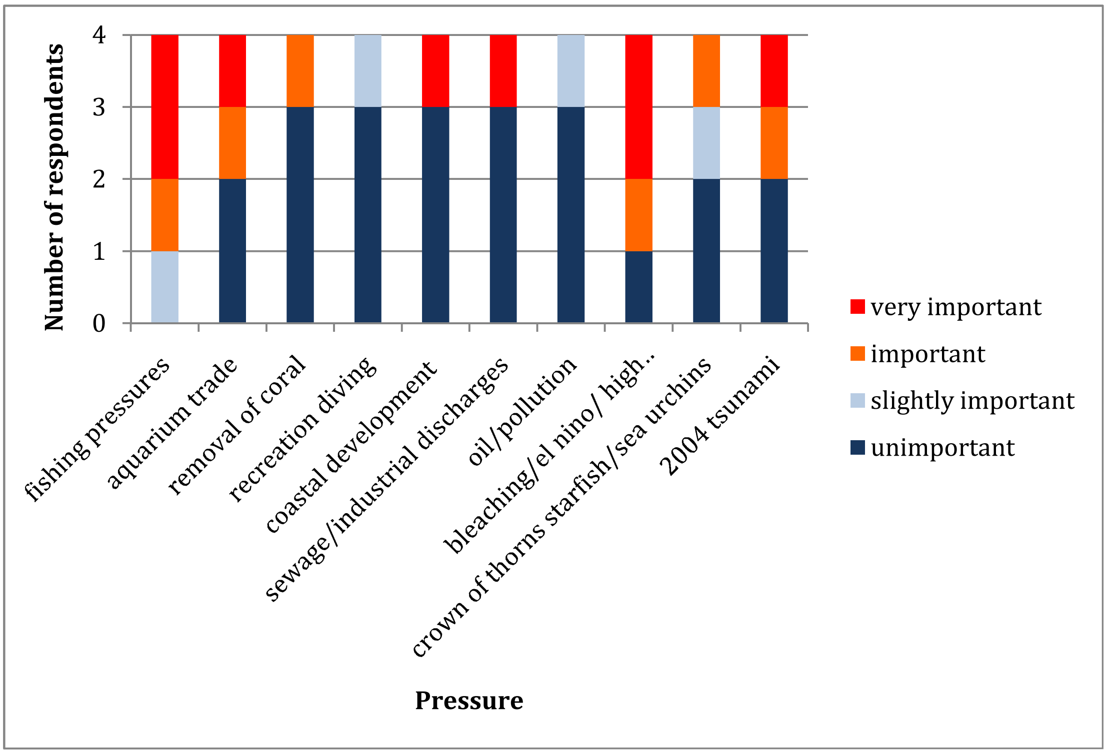


Figure A1.3 Perceived degree to which different pressures on coral reefs influenced changes in coral cover.

- Coral varieties

  One respondent reported a large decrease in coral varieties, two respondents reported a small decrease and one felt there had been no change. The respondent reporting no change was answering the questionnaire for Bar Reef.

  All three of the respondents reporting change felt that bleaching events and El Nino had played a role in the decrease they had observed, and two of the three respondents reporting for Unawatuna and Hikkaduwa felt the 2004 tsunami was an important or very important pressure (Fig A1.4).

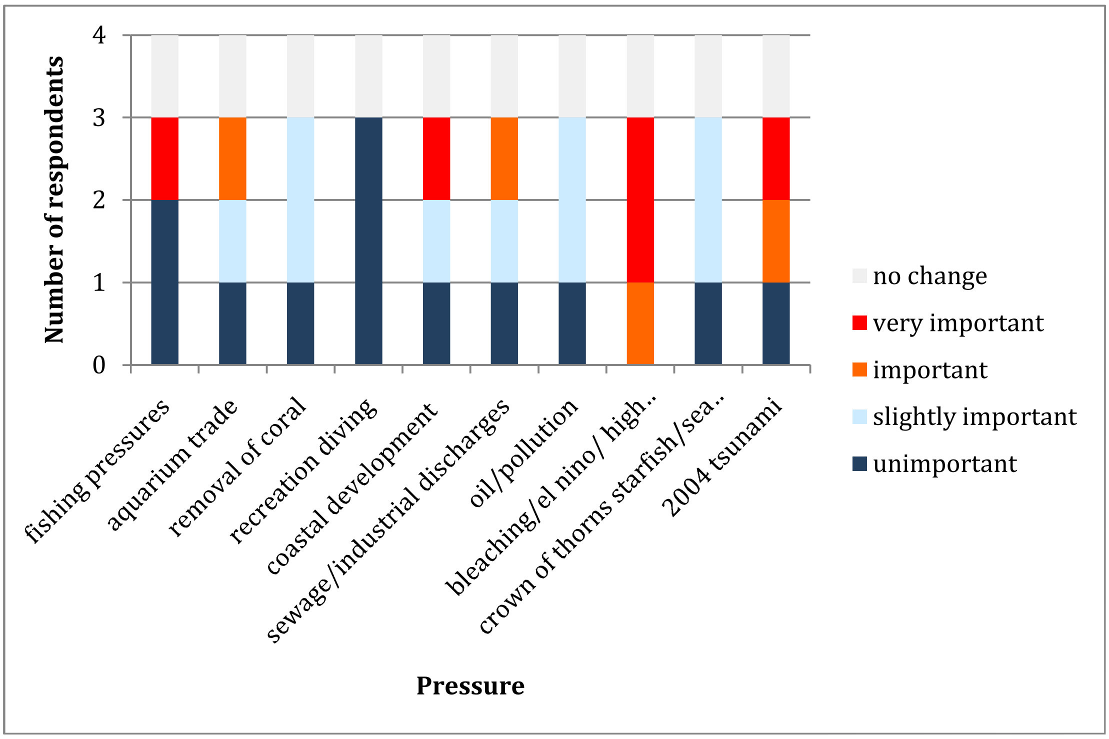


Figure A1.4 Perceived degree to which different pressures on coral reefs influenced changes in coral varieties.

- Algal growth

  Two respondents report a small increase in algal growth and the other two respondents were either unsure or reported no change. Areas with a reported small increase were Beruwala, Bentota, Hikkaduwa, Unawatuna, Weligama and Bar Reef. Fishing pressure was thought an important driver of algal growth by both respondents (Fig A1.5). Diving, crown of thorns starfish and the 2004 tsunami were considered to be unimportant.

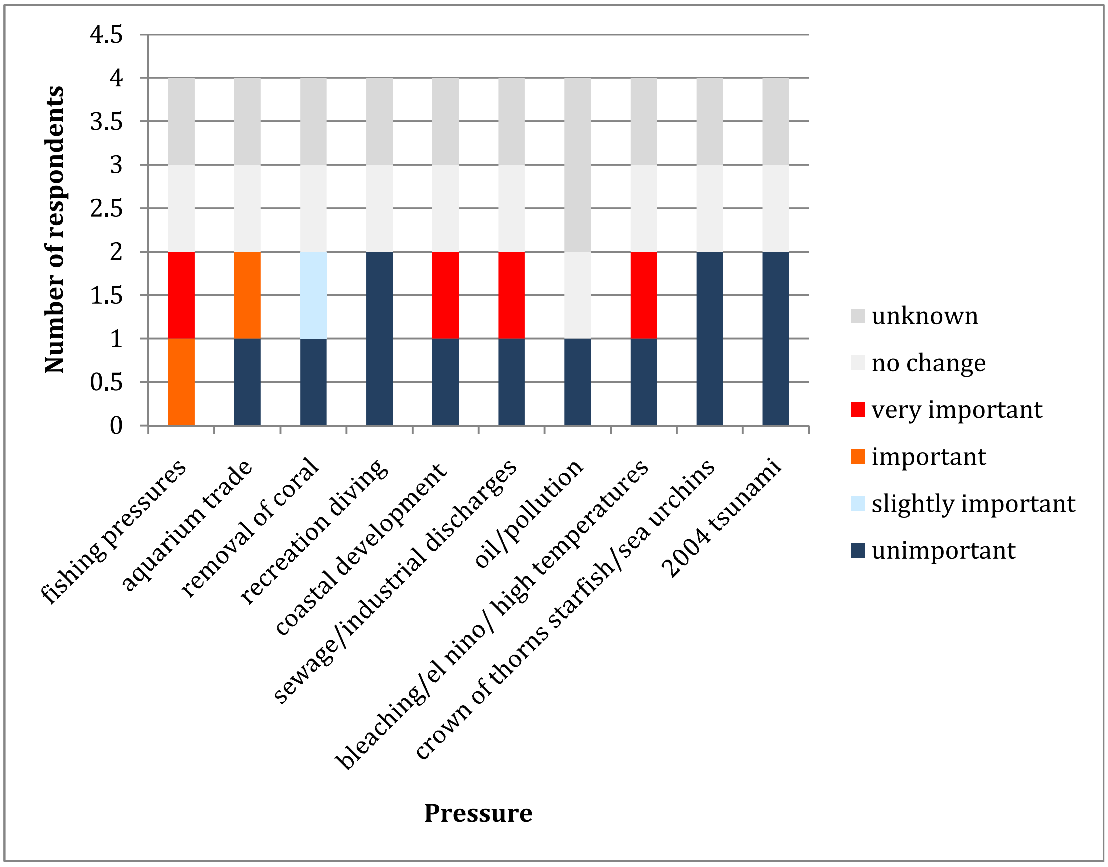


Figure A1.5 Perceived degree to which different pressures on coral reefs influenced changes in algal growth.

- Reef fish abundance

  All four respondents believed that there had been a large decrease in reef fish abundance and three quarters felt fishing pressures played an important role in this decrease (Fig A1.6). Diving was unanimously felt to be unimportant in the decline in reef fish abundance.

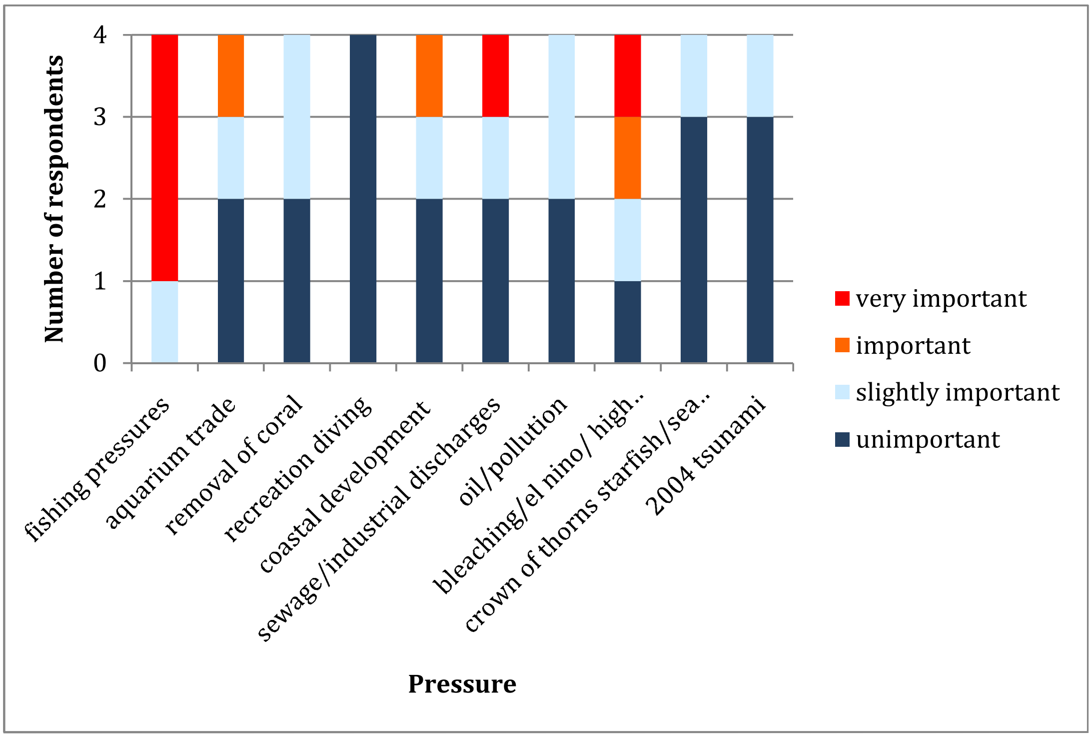


Figure A1.6 Perceived degree to which different pressures on coral reefs influenced changes in reef fish abundance.

- Reef fish varieties

  Two respondents reported a large decrease in reef fish varieties; one reported a small decrease and the remaining respondent believed they had not changed. Where change was evident fishing pressures and bleaching/El Nino were thought to be important or very important in influencing this change (Fig A1.7). The aquarium trade was also identified as important by two respondents.

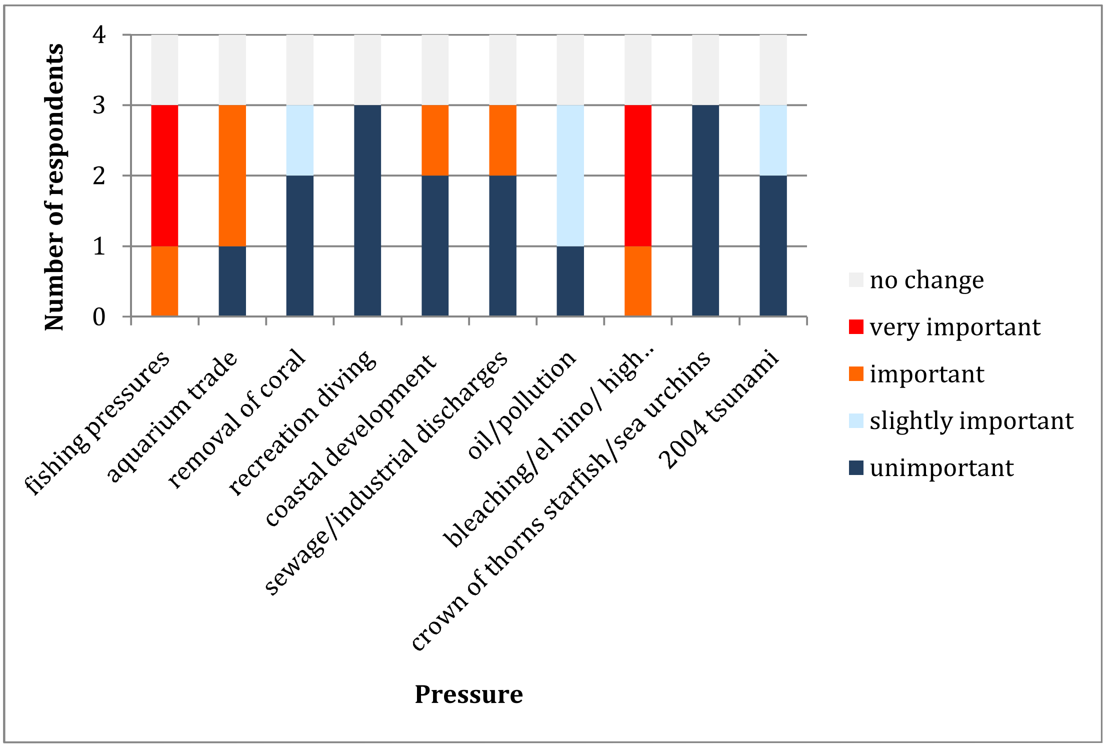


Figure A1.7 Perceived degree to which different pressures on coral reefs influenced changes in reef fish varieties.

- Pelagic fish abundance

  Three of the respondents believed there was a large decrease in pelagic and open water fish and one respondent was unsure. All three attributed this to fishing pressures with all other factors rated only slightly important or unimportant (Fig A1.8).

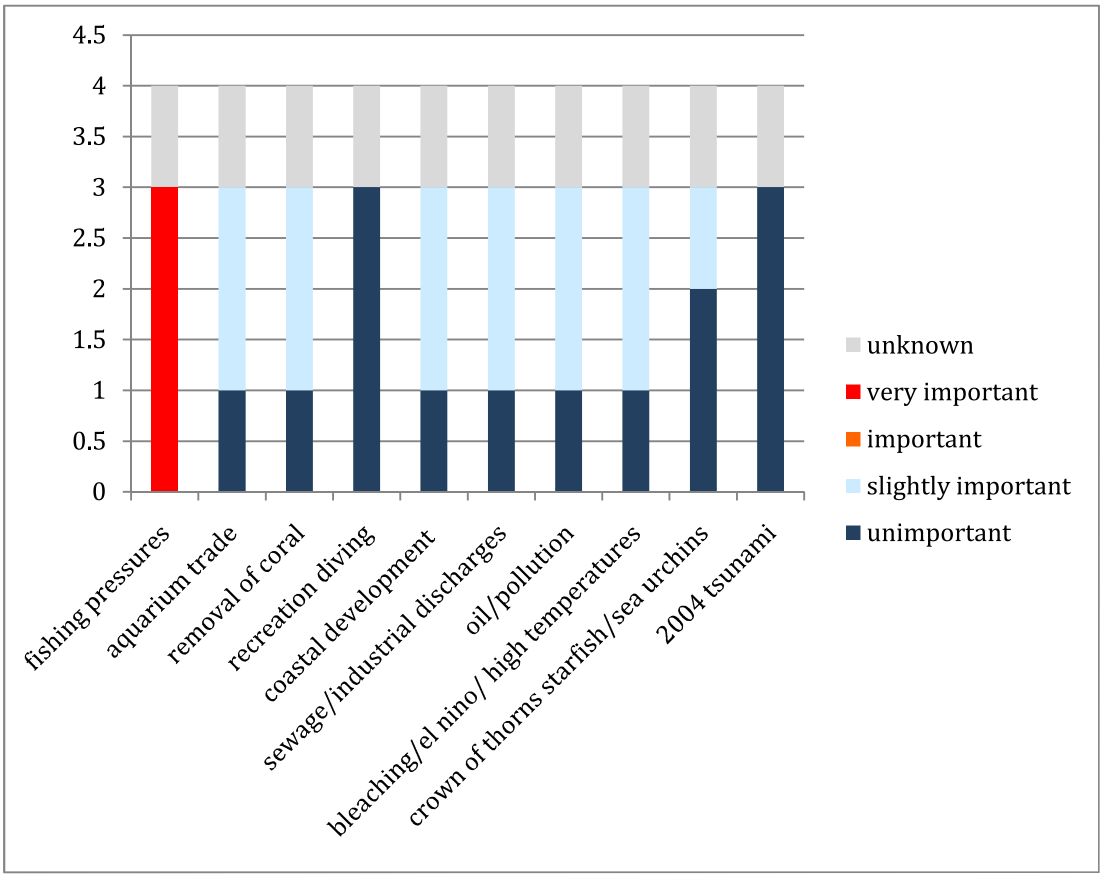


Figure A1.8 Perceived degree to which different pressures on coral reefs influenced changes in pelagic fish varieties.

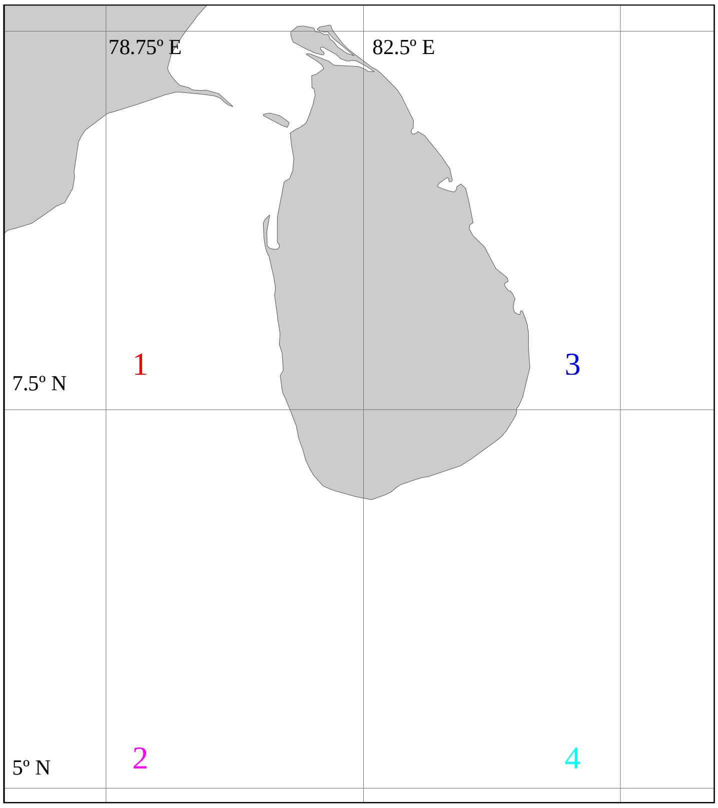
- Additional comments

  Three of the four respondents felt it important to emphasise that protected areas were often not managed properly and two of four respondents felt dynamite fishing was the main pressure on coral reefs within their area.

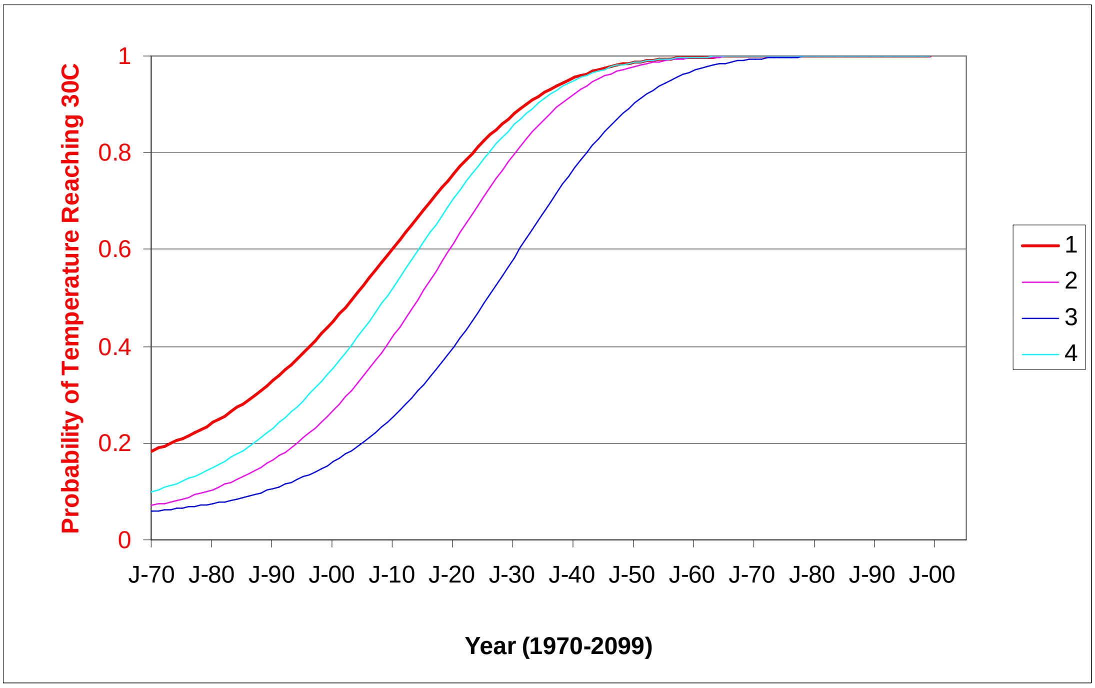
  The questionnaires asked respondents to state years of occurrence for bleaching events. The years 1995, 1996 and 1998 were reported, with some respondents reporting up to 95% mortality within shallow corals during these years. Additionally, one respondent reported a shift from branching *Acropora* spp. to tabular *Acropora* spp. after the 1998 bleaching event.

Appendix 2. Sea surface temperature modelling for Sri Lanka

Using methodology from Sheppard, 2003 four cells (Fig A2.1.i) over Sri Lanka can be analysed. Resultant predictive models for the four HadCM3 cells covering Sri Lanka are shown in Figure A2.1.ii. Despite the close spatial relationship between these cells, the probability of exceeding lethal 1998 temperatures differs. Comparison of these cells when there is a 0.2 probability of temperatures exceeding 30 °C reveals the greatest difference between cells 1 and 3. Cell 1 reached this probability shortly after 1970 whereas cell 3 reached this probability in 2005. In terms of coral reef location, all four cells contain reefs (Fig 2.1) and are therefore vulnerable to temperature excursions.



i.



ii.

Figure A2.1 *i.* Map showing the 4 HadCM3 cells over Sri Lanka. *ii.* Graph showing the probabilities of warmest months of four sites reaching lethal 1998 temperatures over time.

Appendix 3. Questionnaire 2 - Fisheries Sector Questionnaire: Fisher opinions on the Frigate tuna fishery and changes in populations since the 2004 tsunami in Hambantota (2007)

01. Date:…………………………………………….
02. Village:………………………………..……….
03. GN Division:………………………………………
04. Name of the Respondent…………………………………………………
05. Age of the Respondent (in years)…………………………………
06. Do you fish for *Alagoduwa*?

1.yes 2.no

07. How old were you when you caught your best catch of *Alagoduwa*?..........................

08. What was your best ever catch of *Alagoduwa* in one day? Kilos…………………

09. How far offshore from the beach was your best catch?

……..………………….m OR …………………………..km

10. What was the sea water depth where you got you best catch?

……..………………….m OR …………………………..km

11. Using the tape measure provided what was the length of the longest *Alagoduwa* you have ever caught?

………………………. inches

12. How old were you when you caught your largest *Alagoduwa*? …………………………………

13. How many fishing locations for *Alagoduwa* have shown a decrease in catch?

1. 0 2. 1-9 3. 10-19 4. 20+

14. Do you think that fishing catch in general has changed since the 2004 tsunami?

1. Decreased
2. No Change
3. Increased
4. Unsure

15. If fishing catch has changed, what do you think is the main cause?

1. Extra boats provided by tsunami aid money
2. General increase in fishers / new generation of fishermen (not related to tsunami aid)
3. Tsunami damage to fish and marine life
4. Warming seas
5. Other (Specify) ……………………………

16. How many boats were there in this harbour (fishing location) Before Tsunami?
No. of Small boats: ……………………..
No. of Large boats:………………………
No. of multi-day boats: …………………

17. How many boats were there in this harbour (fishing location) After Tsunami?

No. of Small boats: ……………………..

No. of Large boats:………………………

No. of multi-day boats: …………………

Appendix 4. Questionnaire 3 - Fisheries Sector Questionnaire: Livelihood of tsunami affected families in Hambantota and fisher opinions on factors influencing tsunami outcome (2007)

Section 1: Respondent and Area Information

1. Date:…………………………………………………………….

2. Village:………………………………..……………………..

3. GN Division:…………………………………………………..

4. Name of the Respondent……………………………………..…

5. Age of the Respondent (in years)…………………………………

6. Tsunami Impact with and without Mangroves

    1. Tsunami Affected with Mangroves

    2. Tsunami Affected without Mangroves

    3. Tsunami Unaffected with Mangroves

    4. Tsunami Unaffected without Mangroves

7. What were the income sources and monthly incomes (disposable) to the family <u>before</u> tsunami?

Livelihoods	Source of Livelihood	Monthly income (approximate)
1		
2		
3		

8. What are the current income sources and monthly incomes (disposable) to the family as of today?

	Source of Livelihood	Monthly income (approximate)
Main source of Livelihood		
Second source of Livelihood		
Third source of Livelihood		

09. How do you perceive the economic status of your family before and after tsunami?

Economic status	Before tsunami	After tsunami
1. Well – off		
2. Average		
3. Poor		
4. Very poor		

10. Please indicate whether you or your direct family were affected by the tsunami?

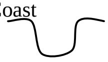
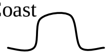
1.Yes
2. No

11. If so, What were the effects of tsunami on the family? (Can have more than one answer)
   1. Lost family members
   2. Family members became sick, disabled, injured (delete irrelevant)
   3. House completely destroyed
   4. House partially destroyed
   5. Lost household goods and furniture
   6. Lost cash and jewellery
   7. Lost boats/canoes/nets (delete irrelevant)
   8. Business/economic activities were affected or destroyed
   9. Damage to agricultural land
   10 Other (specify)………………………..

12. Where was your house located at the time of tsunami?
   1. Within 100 meter zone
   2. Outside 100 meter zone

Section 2: Influence of Ecosystems, Developments and Infrastructure on *Tsunami* Impacts

13 The tsunami as you know had a devastating impact on human life and housing. In your opinion how did natural ecosystems, infrastructure and developments influence the impacts of the tsunami in each of these cases? Please use the scale provided to indicate your views.

	Effect on Human Death Toll					Effect on House Damage				
Presence of Ecosystem, Development etc.	1. Decreased Impacts	2. No Effect	3. Increased Impacts	4. Unsure	5. Not Present	1. Decreased Impacts	2. No Effect	3. Increased Impacts	4. Unsure	5. Not Present
(A) Coral Reefs	1	2	3	4	5	1	2	3	4	5
(B) Seagrass	1	2	3	4	5	1	2	3	4	5
(C) Sand Dunes	1	2	3	4	5	1	2	3	4	5
(D) Mangroves	1	2	3	4	5	1	2	3	4	5
(E) Rivers/Estuaries	1	2	3	4	5	1	2	3	4	5
(F) Straight Coast Sea	1	2	3	4	5	1	2	3	4	5
(G) Convex Coast  Sea	1	2	3	4	5	1	2	3	4	5
(H) Concave Coast  Sea	1	2	3	4	5	1	2	3	4	5
(I) High Beach Slope	1	2	3	4	5	1	2	3	4	5
(J) Hotels	1	2	3	4	5	1	2	3	4	5
(K) Fish/Shrimp Farms	1	2	3	4	5	1	2	3	4	5
(L) Roads	1	2	3	4	5	1	2	3	4	5
(M) Housing	1	2	3	4	5	1	2	3	4	5

Appendix 5. Publications of direct and indirect relevance to thesis